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NATIONAL BUREAU OF STANDARDS REPORT

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THE HEATING PERFORMANCE OF AIR-TO-AIR HEAT PUMPS IN MILITARY HOUSING

by

C. W. Phillips and P. R. Achenbach
Mechanical Systems Section
Building Research Division

Report to
Office of the Chief of Engineers
Bureau of Yards and Docks
Department of the Air Force

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1. Introduction

The National Bureau of Standards conducted a field study of year-round air conditioning systems in a number of Air Force housing projects under the sponsorship of the U.S. Air Force, the Office of the Chief of Engineers, and the Bureau of Yards and Docks. In one part of this investigation the heating characteristics of the air-to-air heat pumps installed at Seymour Johnson and Columbus Air Force Bases were studied. Five dwelling units were selected for study at each air base. Instrumentation was installed in each dwelling unit to determine the amount of electric energy used by the heat pump and each of the other major appliances, the amount of heat delivered to the dwelling by the heat pump and by the other appliances, the heat loss of the dwelling at design outdoor temperature, the coefficient of performance of the heat pump as installed, the indoor and outdoor temperatures, the lowest outdoor temperature at which the heat pump could maintain the desired indoor temperature, the requirements for supplementary resistance heating, energy-usage factors relating energy requirements, severity of the weather, and dwelling size, and corollary information on air leakage of the distribution system. Observations were taken successively at the two air bases for a period of about one month each during the colder winter months.

2. Description of Sample Dwellings

Five dwelling units were selected from the total of 1500 at Seymour Johnson Air Force Base and an equal number were chosen from the total of 480 at Columbus Air Force Base for this study. The sample dwellings at both bases are identified in Table 1 with respect to street address, type of dwelling unit, number of bedrooms, inside floor area, gross exterior wall area, window and door area, ceiling area, perimeter of exterior walls, and volume of heated space.

TABLE 1

IDENTIFICATION OF SAMPLE DWELLINGS

Street Address	Dwelling Type	No. of Bedrooms	Inside Floor Area ft^2	Ceiling Area ft^2	Gross Exterior Wall Area ft^2	Window & Door Area ft^2	Perimeter of Exterior Walls ft	House Volume ft^3
Seymour Johnson AFB								
402 March Lane	A	2	993	993	931	232	116	7954
413 Carswell Lane	B	3	1123	1123	1148	251	143	8995
217 Chanute Road	C	2	1016	1016	943	232	118	8138
215 Chanute Road	D	3	1163	1163	1043	251	130	9316
301 Carswell Lane	E	3	1298	1305	1674	349	193	11190
Columbus AFB								
122 Vernon Ave.	A2D1	2	928	928	819	179	102	7433
117 Caledonia Loop	A3D1	3	1028	1028	889	202	110	8234
119 Caledonia Loop	A3D1	3	1028	1028	889	202	110	8234
116 Florida Ave.	03S1R	3	1298	1298	1356	250	168	10397
118 Florida Ave.	03S3	3	1298	1298	1356	250	168	10397

All of the dwelling units at Seymour Johnson Air Force Base were of single story construction built on concrete slabs on grade. Seven different floor plans were used, designated by type as A to G. The five dwellings selected for study were of types A to E which comprised all but 12 in the entire development. Dwelling unit types A to D were of duplex construction, having rectangular floor plans for each unit. The two units had a common end wall in some cases, and in other cases were joined only at a corner. House type E was L-shaped and of detached construction. In the sample used for this study, dwelling unit A had a common end wall with another unit, dwelling unit B was corner-connected with another unit, and dwelling units C and D were the two units of a duplex structure with a common end wall. Figure 1 is a front view of units C and D in the sample, and Figure 2 is a front view of the detached type E house. Figures 3-7, inclusive, are floor plans of houses type A to E, respectively, showing the room arrangement, the doors and windows, and the location of the heat pump and air distribution system.

The exterior walls of the sample dwelling units at Seymour Johnson Air Force Base were principally of brick veneer construction, although selected parts, which varied from unit to unit, were finished on the exterior with grooved plywood. The stud spaces in the frame walls were filled with 3-inch batts of glass fiber insulation, covered on the inside with 1/2-inch gypsum wallboard and on the outside with 5/16-inch exterior plywood sheathing and waterproof building paper. The brick veneer was separated from the sheathing by a 1-inch air space, whereas the exterior grooved plywood finish was supported on 3/4-inch furring strips. The reinforced concrete floors were 4 inches thick laid over a waterproof membrane and a 4-inch layer of crushed stone. The floor was insulated at the edge with 1-inch thick rigid insulation in an L shape reaching 2 feet inward from the edge and vertically upward at the edge to the floor surface level. The floor slab rested on the foundation. The floor covering was ceramic tile in the bathroom and vinyl tile in the remainder of the dwelling, in types A to D, inclusive. The floors of the entrance hallway and living room were of slate and carpet over wood, respectively, in the sample type E house, but otherwise the floor covering was like that in the other dwellings. Except for the living room and dining room in the type E house, ceilings were made of 2- by 6-inch joists with 1/2 inch of plaster finish on 1/2-inch gypsum on the under side, and 6 inches of glass fiber insulation between joists. In the type E house, the ceiling finish was applied to the under side of the 2- by 8-inch roof rafters over the living room and dining room. Insulation, 6 inches thick, was placed between the roof rafters for these two rooms. Roofs were built to a slope of 2 1/2 inches per foot. The roof rafters were covered with 5/8-inch plywood sheathing, 4-ply built-up roofing, and gravel. Attic spaces were ventilated by slatted louvers in each gable, and by continuous screened openings in the under side of the overhanging eaves. Single-glazed aluminum-frame windows with horizontally sliding sash were used throughout all dwelling types. Exterior doors were of wood, 1 3/4 inch thick, with solid core.

All of the dwellings at Columbus Air Force Base were of single-story construction built on reinforced concrete slabs on grade. Four different floor plans were used, with several variations in exterior finish for each floor plan. The dwelling units for airmen were of duplex construction with a common end wall, whereas some of the dwellings for officers were detached and others were of duplex construction. The three variations of the two-bedroom dwellings for airmen were designated as types A2D1, A2D2, and A2D3, whereas the corresponding designations for the three-bedroom dwellings for airmen were A3D1, A3D2, and A3D3. The corresponding duplex dwellings for officers were identified as O2D1, O2D2, and O2D3 for 2-bedroom units and O3D1, O3D2, and O3D3 for 3-bedroom units. The officers' detached houses had three or four bedrooms. The variations in the 3-bedroom houses were designated as types O3S1, O3S2, and O3S3 if the kitchen and carport were on the left end, and types O3S1R, O3S2R, and O3S3R if the kitchen and carport were on the right end of the structure. The variations in the 4-bedroom detached officers' houses were designated as types O4S1, O4S2, O4S1R, and O4S2R. Table 1 indicates that two type A3D1 dwellings and one each of types A2D1, O3S1R, and O3S3 were used for the sample. Figures 8 and 9 are front views of the types A3D1 and O3S3 dwellings, respectively. Figures 10-12, inclusive, are floor plans of dwelling types A2D1, A3D1, and O3S3, respectively, showing the room arrangement, the doors and windows, and the location of the heat pump and air distribution system.

The exterior walls of all the sample dwellings at Columbus Air Force Base, except type O3S3, were of frame construction with different portions finished on the exterior with brick veneer, shake siding, vertical siding, or exterior grade grooved plywood. The locations of the portions using these different finish materials were the same for all dwellings of the same floor plan with a given letter and number designation. In house type O3S3, cavity brick walls 8 inches thick were used for a part of the exterior walls. The stud spaces in the frame walls contained glass fiber batts 2 inches thick with a vapor barrier on the inside. The interior wall finish consisted of 3/8-inch rock lath and 3/4 inch of plaster. The studs were covered on the outside with 3/4-inch plywood sheathing and grade D building paper. The exterior brick were separated from the sheathing by a 1 1/4-inch air space, whereas the 3/4-inch grooved plywood, the vertical siding, and the lapped shake siding were applied directly on the sheathing. The reinforced concrete floors were 4 inches thick laid over a 6-mil plastic membrane and a 4-inch layer of washed gravel fill. The slabs were thickened at the edges to provide integral concrete footings. Where shake siding, vertical siding, or grooved plywood was used as an exterior wall covering, vertical edge insulation 1 inch thick was applied to the concrete floor to a depth of 8 inches below grade. The floor covering was ceramic tile in the bathrooms, grease-proof asphalt tile in the kitchens, and parquet wood tile in the other rooms of all dwellings. Trussed rafters, spaced at 2-foot intervals, were used in the ceiling and roof construction. A 2-inch thickness of glass fiber insulation was placed between the ceiling joists with a vapor barrier on the under side. The ceiling finish consisted of 3/8-inch rock lath and 3/4 inch of plaster. The roofs were built to a slope of 3 in.

per foot. The roof sheathing was 3/4-inch plywood which was covered with 15-lb roofing felt and asphalt shingles. Attic spaces were provided with slatted louvers in each gable, but these were sealed during the winter. Screened openings were provided on the under side of the overhanging eaves, and these were not sealed. Single-glazed aluminum-frame windows, with one horizontally-sliding sash and one fixed sash, were used in all dwellings. Exterior doors were of wood, 1 3/4 inches thick, and were solid core except for the door leading to the terrace. Only the kitchen door contained a glass panel.

3. Description of Mechanical Equipment

3.1 Seymour Johnson Air Force Base

A single air-to-air heat pump of the split type was installed in each dwelling unit at Seymour Johnson Air Force Base. The indoor and outdoor units in each of the sample houses are identified in Table 2, which also tabulates the compressor horsepower and the nominal capacity of the supplementary resistance heaters for each installation. The location of the indoor and outdoor units and the supply and return ducts in the sample houses is shown in the floor plans in Figures 3-7, inclusive.

The indoor units in dwellings A to D at Seymour Johnson Air Force Base were installed in the attics over the hallways at approximately the center of the dwelling and adjacent to the access door for the attic. Figure 13 shows such an installation as viewed at an upward angle through the open access door to the attic. The supply air from the indoor unit was carried to the several rooms through ducts, part of which were supported on the ceiling joists over the insulation, and part of which were furred down from the ceiling. The air was discharged into the rooms through high sidewall grilles in each case. Ducts in the attic were insulated with glass fiber with paper vapor barrier, sealed at the joints. The return air entered a louvered grille near the floor level and flowed upward to the attic through a passage provided in a part of a space originally planned as a closet. The glass fiber air filter was attached to the back of the louvered grille. The blower was on the downstream side of the indoor coil, and the supplementary resistance heaters were located in the discharge side of the blower.

The indoor unit for the E type house at Seymour Johnson Air Force Base was installed in a closet adjacent to the front hall and living room. Figure 14 shows this installation. The supplementary resistance heaters were located in the separate housing mounted on top of the unit casing. The supply air plenum extended through the closet ceiling into the attic where short ducts connected the plenum to high sidewall grilles on interior partitions in the living room and dining room. The supply air to the kitchen, 3 bedrooms, and 2 baths flowed through short attic ducts and then through elbows to ducts furred down from the ceiling and to high sidewall grilles on an interior partition in each room. The attic ducts and plenum were covered with glass fiber insulation and a vapor barrier. The return

TABLE 2

IDENTIFICATION OF HEAT PUMP COMPONENTS IN
DWELLING UNITS AT SEYMOUR JOHNSON AFB

Type of Dwelling Unit	Street Address	Outdoor Unit: Mathes Co. Model No.	Outdoor Unit: Comp. Motor Size hp	Indoor Unit: Model No.	Indoor Unit: Supp. Resistance Heater Cap. kW
A	402 March Lane	27-HAR-IE-HP	2.5	38LEB-HP	7.2
B	413 Carswell Lane	38-HAR-IE-HP	3.6	38REB-HP	3.6
C	217 Chanute Road	27-HAR-IE-HP	2.5	27REB-HP	7.2
D	215 Chanute Road	27-HAR-ID-HP	2.5	27REB-HP	7.2
E	301 Carswell Lane	38-HAR-IE-HP	3.6	38VEB-IE-HP	
				H-20*	7.2

*The resistance heaters were in a separate housing in this unit.

air entered the utility closet through louvers in the closet door and through a low-wall grille in the living room. The glass fiber air filters were located in the return air openings of the indoor unit.

In all indoor units at Seymour Johnson Air Force Base, the condensate was collected in a pan forming the bottom of the unit; it was conveyed by a pipe to the floor slab level and thence to the outside through a fiber pipe embedded in the floor slab with a slight slope in the direction of flow. In dwelling types A to D, inclusive, the room thermostats were located in the branch hall to the bathroom, whereas it was located on an inside partition at the entrance end of the hallway serving the bedrooms in the type E house. All thermostats were located at a height of 5 feet above the floor.

The outdoor unit for all dwellings at Seymour Johnson Air Force Base was located on a concrete base a few feet from the back side of the house, as illustrated in Figure 15. The outdoor air inlet faced the house and the discharge was on the opposite side of the steel cabinet. The refrigerant lines connecting the indoor and outdoor units ran underground through asphalt impregnated fiber duct, whereas the electric service was enclosed in metal conduit.

Each dwelling unit was equipped with a water heater, clothes dryer, automatic washer, dishwasher, cooking range, and refrigerator, all electrically-operated. The water heater had a storage capacity of 66 gallons in the type E dwelling and 52 gallons in the other four sample houses. An upper heating element of 3 kW nominal heating capacity and a lower heating element of 2 kW heating capacity was used in each water heater. An interlock prevented the two elements from being energized simultaneously. Each clothes dryer was equipped with a 1/3-hp motor and a heater of either 4.6 or 5.6 kW capacity, depending on the type of dwelling unit. Each dishwasher was equipped with a 1/6-hp motor and a heating element of 0.56 kW capacity.

3.2 Columbus Air Force Base

A single unitary air-to-air heat pump was installed in each dwelling unit. The same model, General Electric Company WT-44C1, equipped with a 5-hp compressor motor, was used in every dwelling. Each unit was provided with supplementary resistance heaters with a capacity of 10 kW. The heat pump was installed in a utility closet which was adjacent to the front door in dwelling types A3D1, O3S3, and O3S1R and which was at the rear of the dwelling in type A2D1. The location of the heat pump unit and the arrangement of the supply and return air ducts in the sample dwellings are shown on the floor plans in Figures 10-12, inclusive. Figure 16 is a view of the complete heat pump as seen through the door of the utility closet. Figure 17 is a view from the same position with the front of the metal casing of the heat pump removed to show the arrangement of the major components of the system.

The warm air supply ducts in dwelling types A2D1 and A3D1 crossed the utility closet beneath the ceiling and then passed through the closet wall to the space above the furred ceiling which was provided over the entire hall and entrance area. The furred ceiling was not closed on the upper side, but the supply ducts and furred ceiling were covered by the ceiling insulation. The warm air was introduced into each room through a high sidewall register and into the entrance hall through a ceiling diffuser. The warm air supply system to the bedrooms in the officers' duplex dwellings was similarly arranged. The attic ducts in the officers' detached dwellings delivered warm air to the living room, dining room, and kitchen through short wall stacks and high sidewall registers. Only the duct to the kitchen contained a volume damper. The return air entered a louvered grille off the hallway opposite the utility closet in all dwelling units. It traversed a closet through a duct near the floor in dwelling types A2D1 and A3D1 to enter the utility closet, whereas in dwelling types 03S3 and 03S1R the utility closet adjoined the hall so the return duct only penetrated the common wall between these two spaces. The glass fiber air filter was attached to the return air opening of the heat pump unit in each installation and there was little space between the air filter and the face of the indoor coil. The indoor blower was on the downstream side of the indoor coil, and the supplementary resistance heaters were located on the discharge side of this blower.

Each dwelling unit was equipped with a water heater, clothes dryer, automatic washer, dishwasher, cooking range, electric resistance heater in the bathroom, and a refrigerator, all electrically-operated. The water heater had a storage capacity of 50 gallons and was equipped with upper and lower heating elements, each with a capacity of 4.5 kW. An interlock prevented the two elements from being energized simultaneously. The total connected load of other major appliances was as follows: clothes dryer, 5 kW; dishwasher, 1.5 kW; bathroom heater, 1.5 kW; and cooking range, 12.7 kW.

4.0 Test Apparatus

Eight watthour meters were installed in each sample dwelling at Seymour Johnson AFB and nine in each sample dwelling at Columbus AFB to integrate the energy used by each of the major appliances and the total energy used by the dwelling. In the former site the meters were installed on the rear of the dwellings and in the latter site, in the storage rooms at the end of the dwellings, as illustrated in Figures 18 and 19, respectively. The meters were wired to measure the energy used by the following loads:

(a) Total house load
(b) Total heat pump load
(c) Heat pump compressor and blower motors
(d) Supplementary resistance heaters in the heat pump
(e) Cooking range
(f) Hot water heater
(g) Clothes dryer
(h) Lighting and miscellaneous loads
(i) Bathroom heater (Columbus AFB only)

At Seymour Johnson AFB, the smallest graduation on the last dial of seven of the watthour meters represented 100 watthours, whereas a corresponding interval on the eighth meter, which measured the energy use of the supplementary resistance heaters, represented 10 watthours. At Columbus AFB, the smallest graduation on the meters for the total house load and the total heat pump load represented 10 kWh, the smallest graduation on the meter for the supplementary resistance heaters represented 0.01 kWh, and a corresponding interval on the other six meters represented 1 kWh. Running time meters were installed on the compressor motor circuit in each sample dwelling at both sites to indicate the cumulative operating time of the heat pump compressor. A recording voltmeter was installed on the incoming electric lines for each dwelling at Seymour Johnson AFB, and on one dwelling in Columbus AFB. Pressure gages were installed on the suction and discharge lines of the compressor for each dwelling unit at Seymour Johnson AFB, but these instruments were not used at Columbus AFB because the heat pump systems were of the sealed type.

A 16-point recording potentiometer was installed in the storage room of each sample dwelling unit at both sites for continuous recording of temperature at selected places, in the air distribution system, refrigerant circuit, living space, attic, and outdoors, using copper-constantan thermocouples of 30-gage wire. A pyrheliometer was used to measure incident solar radiation at each site. A typical location of the outdoor air thermocouple and the pyrheliometer is shown in Figure 20. A micromanometer was used to measure impact pressures and static pressures at selected places in the air distribution system.

5.0 Test Procedure

Observations of all of the watthour meters at each dwelling unit were taken and recorded at 2-hour intervals on a staggered time basis for the duration of the study, approximately one month at each site. The running time meters and pressure gages were read on the same time schedule as the watthour meters. In a typical installation the potentiometer recorded air temperatures at the return grille of the air distribution system, at the inlet to the indoor and outdoor coils, at the inlet to the indoor blower, in the discharge plenum of the indoor unit, at the center of one or more rooms 6 feet above the floor, at two stations in the attic midway between ceiling insulation and roof ridge and 1/3 the distance from each end of the attic space, and at one outdoor station near the roof level at the end of the carport, as well as the surface temperature of the case of the room thermostat. The temperatures of the refrigerant vapor line were also recorded at the compressor suction, and near its connections to both the indoor and outdoor coils. Multiple thermocouple junctions in parallel were used at all stations in the indoor air distribution circuit and at the inlet to the outdoor coil to obtain a better average of the air temperatures. In some instances the air temperatures upstream and downstream of the indoor coil were recorded more frequently than the other temperatures in order to obtain a more detailed record of the change in air temperature during cyclic operation of the heat pumps.

Calibration tests were made at the beginning of the investigation in each dwelling unit to measure the rate of air circulation through the indoor coil and air distribution system. These tests consisted of measuring the temperature rise produced in the circulated air when one or more elements of the supplementary resistance heaters were energized and the energy input was measured. The housing and supply plenum of the heat pump were well insulated so the heat loss through this short section was neglected in computing the air circulation rate. Clean air filters were used in the system during the calibration tests and the supply registers and grilles were in the same position as for normal operation. In the type E dwelling at Seymour Johnson AFB a check test of air circulation rate was made by connecting a straight duct, about 10 feet long and 14 inches in diameter, to the return air grille and using a Pitot tube to measure air velocity in the straight duct, while simultaneously measuring air temperature rise produced by a measured electric energy dissipation in the supplementary resistance heaters. This comparison was made in a system known to have little extraneous air leakage into the duct system or indoor unit casing.

During the course of the tests at each air base, it became obvious that an appreciable amount of air was being drawn into the return air duct system from the attic. At Seymour Johnson AFB the leakage occurred principally where the return duct was fitted into the ceiling of the closet that was converted into a return-air passage as a modification of the original plans. At Columbus AFB the leakage occurred between the attic and the utility closet where the main supply duct passed through the utility closet wall into the space above a section of furred ceiling. The opening in the wall was larger than the duct, leaving a passage for air leakage as indicated by the darkest area at the right side of Figure 21. Therefore, near the end of the investigation at each site some measurements were made from which the order of magnitude of the air leakage could be determined. For this purpose, the return air grille and all of the supply grilles except one were covered to prevent any air flow through them. A 6-inch diameter duct was fitted to the one supply grille with an airtight connection. With the indoor fan running, all of the air that leaked into the return system from the attic was discharged through the 6-inch duct, assuming that no air leakage occurred in the discharge duct system. By measuring the air flow rate in the 6-inch duct, a minimum value of air leakage could be determined. Static pressures were measured downstream of the return air grille and in the supply plenum under the special conditions just described and also under normal operating conditions, so corrections to the measured air leakage could be made to account for difference in the pressure conditions at the points of leakage. The relation between the temperatures at the return air grille, at the inlet to the indoor coil, and in the attic during normal operating conditions were also used to compute the probable amount of air leakage from the attic.

Hourly data on dry-bulb and wet-bulb temperatures, and wind velocity and direction, and the total precipitation for consecutive 6-hour intervals were obtained from the weather station at each air base for the period covered by the tests.

6.0 Heat Pump System Performance

6.1 Steady State Heating Capacity

The heating capacity of the compression system in the heat pump in each sample dwelling was determined for a range of outdoor temperature by observing the temperature rise produced in the circulated air as it passed through the indoor coil. The test period selected for these determinations was usually between midnight and 6:00 a.m. when outdoor temperatures were reasonably steady and when the indoor temperatures were typically undisturbed by the activities of the occupants. The computation of steady-state heating capacity was based on the recorded temperature rise of the circulated air between inlet and outlet of the indoor unit near the end of a running period and when the supplementary resistance heaters were not energized, and the rate of air circulation which was determined in separate tests using the supplementary resistance heaters alone as a heat source.

The principal data required for computing heating capacity and coefficient of performance of the heat pump and performance factor of the system are summarized for a range of outdoor temperature in Tables 3-7, inclusive, for the five sample dwellings at Seymour Johnson AFB, and in Tables 8-11, inclusive, for four sample dwellings at Columbus AFB. The heating capacity for the heat pump in the type A2D1 dwelling at 122 Vernon Avenue at Columbus AFB was not determined because the running periods of the heat pump were too short to produce a representative temperature rise in the air. A typical set of operating data is tabulated for outdoor temperature increments of about 5°F rather than all of the values obtained at each outdoor temperature level. The heating capacity of each of the nine units is plotted against outdoor temperature in Figure 22. The dry-bulb temperatures shown in Tables 3-11, inclusive, and plotted in Figure 22 are those recorded at the weather stations at the two air bases for the corresponding time of observation. The outdoor temperatures observed adjacent to the sample dwellings did not differ from the airport temperatures more than 1 degree in most cases, although the differences were occasionally greater than this because of local wind currents or solar radiation.

The lower group of six curves in Figure 22 applies to the heat pumps at Seymour Johnson AFB, whereas the upper group of three curves with a discontinuity at midlength represents the performance of four identical heat pumps used at Columbus AFB. It will be noted that the steady-state heating capacity of each of the heat pumps at Seymour Johnson AFB increased with rising outdoor temperature. The increase was approximately linear with outdoor temperature and ranged from 25 percent to 50 percent for the temperature range from 20°F to 50°F. The outdoor units of the heat pumps in dwelling types A, C, and D had similar compressor displacements and the indoor units in dwelling types C and D were identical. The heating capacities of these three systems did not differ greatly as shown in Figure 22. Dwelling types B and E had identical outdoor units

and similarly rated indoor units installed in them, but their measured capacities were different. Two capacity curves are shown in Figure 22 for dwelling E. The lower curve represents the capacities observed during the early part of the test period and the upper curve represents the capacities observed later after repair and maintenance operations were performed. After determining that the system did not appear to be developing its full capacity, the capillary tube on the indoor unit was replaced and the system was recharged with refrigerant. The improved performance is indicated by the comparison of the two capacity curves in Figure 22.

The heat pumps installed in the dwellings at Columbus AFB were three-cylinder compressors equipped with a hydraulic device to lift the suction valve on one cylinder on a rising outdoor temperature between 30 and 40°F to reduce the capacity of the system. The data in the upper part of Figure 22 indicate that the heating capacity of the heat pump units in the sample dwellings ranged from about 40,000 to 45,000 Btu/hr at an outdoor temperature of 15°F. Based on the few data taken at outdoor temperatures between 15°F and 30°F, the heating capacity of the sample units appeared to increase at a rate of about 5,000 Btu/hr for a 10-degree rise in outdoor temperature in this outdoor temperature range, for which the compressors were functioning as 3-cylinder compressors. The data in Figure 22 also indicate that the compressors in the four sample houses operated as 2-cylinder compressors at outdoor temperatures above 32°F. The discontinuities in the capacity curves for the heat pumps in the type 03S1R house and the two A3D1 type dwellings indicate that these units experienced a decrease in capacity of 5500 to 7500 Btu/hr when changing from 3-cylinder to 2-cylinder operation. The rate of increase in compressor capacity with increase in outdoor temperature was about the same for 2- and 3-cylinder operation.

The observed values of steady state heating capacity for the heat pumps at Columbus AFB are somewhat scattered for any given dwelling. Some values obtained at Seymour Johnson AFB also deviate from the curves drawn through most of the plotted points. Such deviations could be caused by variations in air flow rate through the indoor coil resulting from dust accumulation on the air filter, by the effects of wind on the heat transfer in the outdoor coil, by variations in the indoor temperature level, and by other abnormalities in operating conditions.

6.2 Air Flow Rate

The air flow rate through the indoor coil of each heat pump was measured using the supplementary resistance heaters as a calibration mechanism. The air flow rate was computed from the density and specific heat of the air, the temperature rise produced by the resistance heaters, and the electrical energy dissipated in the resistance heaters. Table 12 shows a typical set of results from the dwelling at 215 Chanute Road at Seymour Johnson AFB. Separate tests were made with one to four resistance elements energized, and with only the circulating fan adding energy to the air stream. The table shows that the computed air circulation rate ranged from 934 CFM with four heating elements energized to

1003 cfm with one element energized, corresponding to an average of 956 cfm. The air flow rate computed from the fan energy only should be discounted because the observed temperature rise of about 0.7°F was too small for precise measurement under these conditions. A sixth determination of the air flow rate was made with the pressure drop across the air filter arbitrarily increased from 0.11 to 0.2 in. W.G. to simulate a reasonable dust load on the filter. A comparison of the test results at the two levels of pressure drop across the filter indicated that an increase in pressure drop of 0.09 in. W.G. reduced the air flow rate about 10 percent. The measured air flow rates through the indoor units of the ten sample houses are summarized in Table 13.

The precision of this method for determining air flow rate would be affected by the heat loss from the insulated casing of the heat pump upstream of the discharge temperature-measuring station, as well as the extent to which radiation from the heating elements affected the thermocouple indications. The thermocouples at both the inlet and outlet stations were out of sight of the heating elements, thus minimizing the radiation effect. The computed air flow rate did not always decrease with increasing heat input in every unit, as is indicated in Table 12.

In one dwelling, simultaneous determinations of the air circulation rate were made using the supplementary resistance heaters for one calculation and Pitot tube measurements of velocity in a straight section of duct connected to the return air grille as a second method. The two results differed by only 1.6% in this case. However, this method was not employed in other dwellings to determine the air circulation rate because the leakage of air into the return duct from the attic would have prevented a direct comparison. The average of the values of air circulation rate determined for the several tests with different numbers of the supplementary resistance heaters energized was used in calculating the steady state heating capacities of the heat pumps as summarized in Tables 3-11, inclusive.

6.3 Operating Time of Heat Pumps

The running time meters attached to the compressor circuits in the sample dwellings integrated the hours of operation of the compressors. The meters were graduated to tenths of an hour and estimates of one-hundredth hour were possible. The running time meters totalled all of the operating time of the compressors including the defrosting time, which comprised a very small part of the total operating time except during rainy weather when the outdoor temperature was a little above 32°F. The heat pumps at each base were equipped with automatic defrosting controls. At Columbus Air Force Base the defrost cycle was initiated by a pressure switch actuated by an increasing air pressure

TABLE 3

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
A TYPE DWELLING, 402 MARCH LANE
SEYMOUR JOHNSON AIR FORCE BASE

Test No.		1	2	3	4	5	6	7	8	9
Outdoor Temperature, D.B.	°F	20.1	25.0	30.4	35.0	40.4	45.1	50.0	53.4	62.7
Outdoor Temperature, W.B.	°F	19.0	22.0	26.7	30.5	34.8	36.4	44.2	52.4	52.1
Barometric Pressure	In Hg	30.18	30.02	29.95	30.16	29.97	30.00	29.60	29.80	29.92
Air Temperatures										
Return Grille	°F	70.7	70.8	73.1	73.2	73.5	74.0	76.0	74.0	76.0
Indoor Coil Inlet	°F	65.7	66.3	67.8	68.8	70.8	70.5	73.5	71.5	74.6
Indoor Blower Inlet	°F	79.7	81.3	82.9	84.7	88.0	89.0	90.8	90.8	92.3
Supply Plenum	°F	79.7	81.0	82.8	84.6	88.8	88.5	91.5	91.2	93.0
Attic	°F	37.7	40.6	45.5	46.7	50.8	54.5	57.0	56.5	56.5
Temperature Difference, Coil Inlet to Supply Plenum	°F	14.0	14.7	15.0	15.8	18.0	18.0	18.0	19.7	18.4
Air Circulation Rate	cfm	926	926	926	926	926	926	926	926	926
Heating Capacity, Steady Operation	Btu/hr	13800	14400	14600	15400	17400	17400	17200	18900	17600
Power Input to Heat Pump	watts	2840	2870	2970	3220	3340	3390	3340	3570	3270
Heat Equivalent of Power Input	Btu/hr	9690	9800	10140	10990	11400	11570	11400	12180	11160
C.O.P., Heat Pump Compressor		1.43	1.47	1.44	1.40	1.53	1.50	1.50	1.55	1.58
System Performance Factor, Heat Dissipated in Living Space / Heat Equivalent of Power Input		0.92	1.02	0.93	1.01	1.30	1.21	1.29	1.35	1.46
Cumulative Time of Compressor Operation for Determining Power Input	hr	6.0	6.0	6.0	5.5	3.0	3.8	2.5	2.4	0.7

TABLE 4

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
B TYPE DWELLING, 413 CARSWELL LANE
SEYMOUR JOHNSON AIR FORCE BASE

Test No.		1	2	3	4	5	6	7	8
Outdoor Temperature, D.B.	°F	20.0	25.0	29.4	34.0	40.3	44.9	50.1	55.0
Outdoor Temperature, W.B.	°F	19.0	22.0	26.2	31.5	40.1	41.0	48.4	51.8
Barometric Pressure	In Hg	30.15	30.02	30.03	29.92	29.98	29.98	29.85	29.85
Air Temperatures,									
Return Grille	°F	72.8	74.4	74.1	74.1	73.9	74.0	73.8	74.0
Indoor Coil Inlet	°F	65.3	66.8	68.0	68.0	71.4	71.0	71.4	72.2
Indoor Blower Inlet	°F	89.5	92.7	95.5	95.5	97.4	98.3	102.0	105.8
Supply Plenum	°F	88.5	91.8	94.5	94.5	98.4	99.3	102.1	104.5
Attic	°F	40.8	43.2	46.1	46.1	56.8	56.0	57.5	59.0
Temperature Difference, Coil Inlet to Supply Plenum	°F	23.2	25.0	26.5	26.5	27.0	28.3	30.7	33.6
Air Circulation Rate	cfm	970	970	970	970	970	970	970	970
Heating Capacity, Steady Operation	Btu/hr	23600	25200	26500	26400	26900	28200	30200	32900
Power Input to Heat Pump	watts	3787	3953	4144	3981	4491	4474	4611	4988
Heat Equivalent of Power Input	Btu/hr	12930	13490	14140	13590	15330	15270	15740	17020
C.O.P., Heat Pump Compressor		1.83	1.87	1.88	1.95	1.76	1.85	1.92	1.93
System Performance Factor, $\frac{\text{Heat Dissipated in Living Space}}{\text{Heat Equivalent of Power Input}}$		1.24	1.30	1.45	1.50	1.60	1.65	1.77	1.77
Cumulative Time of Compressor Operation for Determining Power Input	hr	6.0	6.0	5.7	5.2	3.5	3.5	2.7	2.5

TABLE 5

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
C TYPE DWELLING, 217 CHANUTE ROAD
SEYMOUR JOHNSON AIR FORCE BASE

Test No.		1	2	3	4	5	6	7
Outdoor Temperature, D.B.	°F	21.0	25.4	29.0	34.8	39.9	44.2	48.6
Outdoor Temperature, W.B.	°F	19.0	23.7	25.4	32.9	39.2	43.0	45.5
Barometric Pressure	In Hg	30.13	30.34	30.31	30.19	29.95	29.81	29.86
Air Temperatures,								
Return Grille	°F	71.1	69.5	70.8	71.2	72.2	75.4	73.6
Indoor Coil Inlet	°F	66.1	64.1	65.7	68.0	69.8	73.1	71.3
Indoor Blower Inlet	°F	83.1	83.0	85.8	89.1	93.8	98.0	93.4
Supply Plenum	°F	83.0	82.8	85.4	88.8	93.1	97.7	94.6
Attic	°F	38.3	40.1	41.3	46.2	51.1	54.8	55.5
Temperature Difference, Coil Inlet to Supply Plenum	°F	16.9	18.7	19.7	20.8	23.3	24.6	23.3
Air Circulation Rate	cfm	873	873	873	873	873	873	873
Heating Capacity, Steady Operation	Btu/hr	15700	17400	18200	19100	21000	22000	21000
Power Input to Heat Pump	watts	2920	2960	3020	3210	3160	3420	3220
Heat Equivalent of Power Input	Btu/hr	9970	10100	10310	10960	10790	11670	10990
C.O.P., Heat Pump Compressor		1.57	1.72	1.77	1.74	1.95	1.88	1.91
System Performance Factor, $\frac{\text{Heat Dissipated in Living Space}}{\text{Heat Equivalent of Power Input}}$		1.11	1.22	1.31	1.47	1.75	1.70	1.72
Cumulative Time of Compressor Operation for Determining Power Input	hr	6.0	6.0	6.0	4.3	3.1	3.7	3.0

TABLE 6

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
D TYPE DWELLING, 215 CHANUTE ROAD
SEYMOUR JOHNSON AIR FORCE BASE

Test No.		1	2	3	4	5	6	7
Outdoor Temperature, D.B.	°F	20.0	25.0	28.5	35.0	39.0	44.0	59.9
Outdoor Temperature, W.B.	°F	19.0	22.0	24.3	30.5	38.5	43.5	58.2
Barometric Pressure	In Hg	30.15	30.02	30.02	30.12	29.87	29.87	29.57
Air Temperatures,								
Return Grille	°F	67.3	69.6	71.5	71.6	71.4	72.2	72.3
Indoor Coil Inlet	°F	63.7	66.4	68.5	69.5	69.4	70.5	71.4
Indoor Blower Inlet	°F	79.0	82.6	85.7	86.6	87.7	91.2	94.0
Supply Plenum	°F	79.0	82.6	85.5	86.6	87.7	91.2	94.3
Attic	°F	33.5	37.6	43.0	41.6	48.6	51.5	55.6
Temperature Difference, Coil Inlet to Supply Plenum	°F	15.3	16.2	17.0	17.1	18.3	22.0	22.9
Air Circulation Rate	cfm	956	956	956	956	956	956	956
Heating Capacity, Steady Operation	Btu/hr	15600	16300	17100	17200	18200	21800	22300
Power Input to Heat Pump	watts	2460	2620	2700	2930	3150	3380	3240
Heat Equivalent of Power Input	Btu/hr	8400	8940	9220	10000	10750	11540	11060
C.O.P., Heat Pump Compressor		1.86	1.82	1.85	1.72	1.69	1.89	2.02
System Performance Factor, $\frac{\text{Heat Dissipated in Living Space}}{\text{Heat Equivalent of Power Input}}$		1.42	1.46	1.52	1.51	1.51	1.63	1.95
Cumulative Time of Compressor Operation for Determining Power Input	hr	6.0	6.1	6.0	6.1	3.7	3.3	2.8

TABLE 7

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
E TYPE DWELLING, 301 CARSWELL LANE
SEYMOUR JOHNSON AIR FORCE BASE

		Before Maintenance						After Maintenance				
Test No.		1	2	3	4	5	6	1	2	3	4	5
Outdoor Temperature, D.B.	oF	32.6	35.1	39.4	48.6	50.3	53.4	21.4	25.9	29.8	38.0	41.2
Outdoor Temperature, W.B.	oF	29.8	33.1	37.2	40.0	41.3	45.0	19.5	23.0	25.0	32.8	35.5
Barometric Pressure	In Hg	30.34	29.77	29.73	30.30	29.78	29.48	30.12	30.02	29.92	29.98	29.95
Air Temperatures,												
Return Grille	oF	74.6	72.4	73.9	76.6	79.8	77.9	72.9	74.0	73.3	74.8	74.5
Indoor Coil Inlet	oF	74.3	72.4	73.2	75.7	79.3	77.4	72.4	72.8	72.3	73.9	73.9
Indoor Blower Inlet	oF	85.9	76.4	89.0	95.5	98.8	98.4	93.7	95.5	95.9	99.8	99.5
Supply Plenum	oF	86.5	86.8	89.3	94.6	99.0	98.6	93.0	94.7	95.2	98.6	98.7
Attic	oF	40.1	49.1	53.1	53.4	63.3	63.3	45.9	45.6	48.0	48.1	53.9
Temperature Difference, Coil Inlet to Supply Plenum	oF	12.2	14.4	16.1	18.9	19.7	21.4	20.6	21.9	22.9	24.7	24.8
Air Circulation Rate	cfm	1,467	1,467	1,467	1,467	1,467	1,467	1,467	1,467	1,467	1,467	1,467
Heating Capacity, Steady Operation	Btu/hr	19,000	22,000	24,500	28,900	29,500	31,700	31,400	33,200	34,600	36,100	37,300
Power Input to Heat Pump	watts	4,040	4,210	4,230	4,150	4,480	4,430	3,890	3,930	4,010	4,290	4,290
Heat Equivalent of Power Input	Btu/hr	13,790	14,370	14,440	14,160	15,290	15,120	13,280	13,410	13,690	14,640	14,640
C.O.P., Heat Pump Compressor		1.38	1.53	1.70	2.04	1.93	2.10	2.37	2.48	2.53	2.47	2.54
System Performance Factor (Heat Dissipated in Living Space / Heat Equivalent of Power Input)		---	---	---	---	---	---	---	---	---	---	---
Cumulative Time of Compressor Operation for Determining Power Input	hr	6.0	5.9	5.3	3.8	3.4	3.4	5.7	6.0	5.8	4.8	3.6

TABLE 8

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
A3D1 TYPE DWELLING, 117 CALEDONIA LOOP
COLUMBUS AIR FORCE BASE

Test No.		1	2	3	4	5
Outdoor Temperature, D.B.	°F	13.6	31.0	32.8	42.4	44.8
Outdoor Temperature, W.B.	°F	13.2	28.9	28.8	40.7	36.2
Air Temperatures,						
At Return Grille	°F	79.4	79.5	81.4	82.6	84.0
Indoor Coil Inlet	°F	73.0	73.9	75.2	77.9	81.0
Indoor Blower Inlet	°F	98.3	99.5	100.8	105.5	111.5
Supply Plenum	°F	99.9	101.5	102.9	107.5	113.9
Attic	°F	39.7	35.8	38.4	56.3	61.5
Temperature Difference, Coil Inlet to Supply Plenum	°F	26.9	27.6	27.7	29.6	32.9
Air Circulation Rate	cfm	1,524	1,524	1,524	1,524	1,524
Heating Capacity, Steady Operation	Btu/hr	41,500	49,920	42,700	45,300	49,700
Power Input to Heat Pump	watts	5,890	5,230	5,150	5,510	5,640
Heat Equivalent of Power Input	Btu/hr	20,100	17,850	17,580	18,810	19,250
C.O.P., Heat Pump Compressor		2.06	2.39	2.43	2.41	2.58
System Performance Factor $\frac{\text{Heat Dissipated in Living Space}}{\text{Heat Equivalent of Power Input}}$		1.57	1.91	1.89	2.03	2.34
Cumulative Time of Compressor Operation for Determining Power Input	hr	3.65	3.30	3.69	1.36	2.04

TABLE 9

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
A3D1 TYPE DWELLING, 119 CALEDONIA LOOP
COLUMBUS AIR FORCE BASE

Test No.		1	2	3	4	5	6
Outdoor Temperature, D.B.	°F	14.2	18.4	32.5	32.5	38.1	46.0
Outdoor Temperature, W.B.	°F	13.8	17.6	31.8	31.8	36.7	37.8
Air Temperatures,							
At Return Grille	°F	78.3	79.5	79.9	78.8	78.6	82.3
Indoor Coil Inlet	°F	71.6	72.5	73.9	72.1	74.2	78.6
Indoor Blower Inlet	°F	99.3	102.0	110.3	103.8	104.0	106.2
Supply Plenum	°F	100.9	104.3	110.3	104.1	104.8	111.7
Attic	°F	42.0	42.7	39.1	39.0	50.2	74.2
Temperature Difference,							
Coil Inlet to Supply Plenum	°F	29.3	31.8	36.4	32.0	30.6	33.1
Air Circulation Rate	cfm	1,350	1,350	1,350	1,350	1,350	1,350
Heating Capacity, Steady Operation	Btu/hr	40,200	43,500	49.070	43,600	41,700	44,800
Power Input to Heat Pump	watts	6,040	6,060	5,420	5,510	5,680	5,800
Heat Equivalent of Power Input	Btu/hr	20,620	20,680	18,500	18,810	19,390	19,800
C.O.P., Heat Pump Compressor		1.95	2.10	2.65	2.32	2.15	2.27
System Performance Factor							
$\frac{\text{Heat Dissipated in Living Space}}{\text{Heat Equivalent of Power Input}}$		1.50	1.64	2.21	1.83	1.84	2.02
Cumulative Time of Compressor Operation for Determining Power Input	hr	3.03	3.25	1.90	2.76	1.39	1.0

TABLE 10

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
03S1R TYPE DWELLING, 116 FLORIDA AVENUE
COLUMBUS AIR FORCE BASE

Test No.		1	2	3	4	5	6
Outdoor Temperature, D.B.	°F	13.9	16.0	28.5	29.8	35.0	42.5
Outdoor Temperature, W.B.	°F	13.5	15.5	27.0	29.2	31.2	37.0
Air Temperatures,							
At Return Grille	°F	75.2	74.8	77.0	74.2	74.6	75.1
Indoor Coil Inlet	°F	70.2	69.9	70.5	70.1	69.9	72.6
Indoor Blower Inlet	°F	99.5	100.6	104.5	98.6	100.2	104.6
Supply Plenum	°F	100.7	101.6	105.0	99.3	101.7	105.5
Attic	°F	45.6	45.2	43.5	44.9	47.4	54.9
Temperature Difference, Coil Inlet to Supply Plenum	°F	30.5	31.7	34.0	29.2	31.8	32.9
Air Circulation Rate	cfm	1,439	1,439	1,439	1,439	1,439	1,439
Heating Capacity, Steady Operation	Btu/hr	44,500	46,100	49,900	42,600	46,400	47,500
Power Input to Heat Pump	watts	6,240	6,310	6,090	5,670	5,760	5,840
Heat Equivalent of Power Input	Btu/hr	21,300	21,540	20,960	19,350	19,660	19,930
C.O.P., Heat Pump Compressor		2.09	2.14	2.38	2.20	2.36	2.38
System Performance Factor $\frac{\text{Heat Dissipated in Living Space}}{\text{Heat Equivalent of Power Input}}$		1.75	1.81	1.95	1.89	2.01	2.20
Cumulative Time of Compressor Operation for Determining Power Input	hr	4.65	5.04	1.15	4.34	3.96	2.26

TABLE 11

STEADY STATE PERFORMANCE OF HEAT PUMP COMPRESSION SYSTEM
03S3 TYPE DWELLING, 118 FLORIDA AVENUE
COLUMBUS AIR FORCE BASE

Test No.		1	2	3	4
Outdoor Temperature, D.B.	°F	34.0	37.2	39.4	47.0
Outdoor Temperature, W.B.	°F	33.5	34.6	36.6	40.9
Air Temperatures,					
At Return Grille	°F	67.2	72.8	72.4	76.6
Indoor Coil Inlet	°F	63.2	65.8	67.3	72.8
Indoor Blower Inlet	°F	89.5	96.4	97.3	104.2
Supply Plenum	°F	90.9	97.4	98.0	104.8
Attic	°F	41.7	44.0	50.2	63.5
Temperature Difference, Coil Inlet to Supply Plenum	°F	27.7	31.6	30.7	32.0
Air Circulation Rate	cfm	1,384	1,384	1,384	1,384
Heating Capacity, Steady Operation	Btu/hr	39,730	44,700	43,300	44,600
Power Input to Heat Pump	watts	5,280	5,250	5,500	5,570
Heat Equivalent of Power Input	Btu/hr	18,020	17,920	18,770	19,010
C.O.P., Heat Pump Compressor		2.20	2.49	2.31	2.35
System Performance Factor $\frac{\text{Heat Dissipated in Living Space}}{\text{Heat Equivalent of Power Input}}$		1.88	1.94	1.93	2.07
Cumulative Time of Compressor Operation for Determining Power Input	hr	1.42	3.60	3.13	2.30

TABLE 12

MEASUREMENT OF AIR CIRCULATION RATE [1]
TYPE D DWELLING, 215 CHANUTE RD., SEYMOUR JOHNSON AFB

		Fan Only	Fan and 1 Strip Heater	Fan and 2 Strip Heaters	Fan and 3 Strip Heaters	Fan and 4 Strip Heaters	Fan and 4 Strip Heaters
Time at Start of Air Flow Test,	hr.	1150	1341	1428	1506	1540	1611
Station Barometric Pressure,	in. Hg	30.28	30.25	30.24	30.24	30.24	30.25
Pressure Drop Across Air Filter,	in. W.G.					0.11	0.20
Outdoor Dry-Bulb Temperature	°F	37.0	38.9	38.1	38.1	37.6	37.6
Outdoor Wet-Bulb Temperature	°F	32.0	32.6	32.4	32.4	32.0	32.0
Outdoor Dewpoint	°F	25.3	23.8	24.0	24.0	24.6	24.6
Return Grille Temperature	°F	69.7	69.3	69.7	70.7	72.0	72.5
Indoor Coil Inlet Temperature	°F	68.2	68.0	68.2	69.2	70.2	69.3
Indoor Blower Inlet Dry-Bulb Temperature	°F	68.8	69.7	71.6	74.1	77.4	77.6
Indoor Blower Inlet Dewpoint [2]	°F	30.3	29.0	28.3	29.6	29.0	29.7
Supply Plenum Temperature	°F	68.9	74.7	81.2	88.4	95.9	97.3
Attic Temperature	°F	49.4	49.7	49.9	50.5	50.5	49.6
Temp Diff., Coil Inlet to Supply Plenum,	°F	0.7	6.7	12.9	19.2	25.6	28.0
Air Density at Blower Inlet,	lb/cu ft	0.0755	0.0754	0.0751	0.0747	0.0742	0.0742
Heat Added to Air,	Btu/hr	1106	7290	13240	19620	25770	25460
Air Flow Rate,	lb/min	110.6	75.5	70.8	70.5	69.4	62.7
Air Flow Rate at Blower,	cfm	1464	1003	942	944	934	844

1/ All tests performed on January 1, 1960.
2/ It was assumed that the relative humidity of the air entering the indoor coil was 5 percent higher than that of the outdoor air at the coil inlet temperature.

difference between the upstream and downstream sides of the outdoor coil; and at Seymour Johnson Air Force Base, by a temperature switch activated by an increasing temperature difference between the outdoor coil and the air entering the coil. In the ten sample houses no operating difficulty was observed with the defrost controls during this study, and the loss of heating time caused by the defrost cycle was minimal. No determination was made of the effect of defrost operation on performance characteristics.

Figures 23 to 27, inclusive, show the relation of operating time to outdoor temperature for the five sample houses at Seymour Johnson AFB, and Figures 28 to 30, inclusive, show similar data for the type 03S3 and 03S1R houses and one of the type A3D1 dwelling units at Columbus AFB. Corresponding data for the other two dwelling units at Columbus AFB were not reported because their occupants consistently lowered the thermostat setting at night, so the indoor temperature level was changing during an appreciable part of the night hours. Each plotted point in these figures represents heat pump operating time during a continuous period of about 8 hours between 2200 hours and 0800 hours when a minimum amount of miscellaneous heat release occurred in the dwellings.

Figures 23 to 30 show that the relation between running time and outdoor temperature can be represented reasonably by a straight line at both housing projects. A discontinuity or change in slope of the operating time characteristic curve would have been expected for the heat pumps at Columbus AFB at the outdoor temperature corresponding to the shift from 3-cylinder to 2-cylinder operation. Such a discontinuity is not evident in Figs. 28 to 30, however, perhaps because of the scattering of the plotted points or the scarcity of data at low outdoor temperatures.

In Figs. 24, 26, 27, 29, and 30 data are plotted for night operation with and without setback of the thermostat. When the setback of the thermostat was no more than 2 - 5°F, the operating time did not differ markedly from that without setback, as indicated in Figs. 26 and 27. A larger setback of the thermostat caused significantly less operating time for the heat pump at a given outdoor temperature, as shown in Figs. 29 and 30.

Although there were few data obtained at outdoor temperatures above 55°F, extrapolation of the straight lines indicate that the highest outdoor temperature requiring heat pump operation ranged from 58.5°F to 65°F in different dwellings, even though these data were taken principally during the normal hours of sleep when other sources of heat generation would be minimal.

By extending the straight lines in Figs. 23 to 30 until they reached the horizontal line representing 100 percent operating time, the balance point for the heat pump in each house was determined.

The balance point for a heat pump is defined as the lowest outdoor temperature at which the compressor system can maintain the desired indoor temperature level with constant operation. In the five sample houses at Seymour Johnson AFB the balance point ranged from about 31°F in the type B house down to about 28.5°F in the type D house, whereas it ranged from 15°F down to about -3°F for the three houses at the Columbus AFB. In the latter case, the balance points were all obtained by extrapolating the observed data. An examination of Figs. 23 to 27 indicates that the balance point varied from day to day. This was to be expected, since the heat loss of a house at a given outdoor temperature varies with wind velocity and direction. Furthermore, no effort was made to limit or control the use of miscellaneous heat-producing equipment inside the houses, except to choose a period of the day for this analysis when such use would normally be small.

It will be noted in Figs. 23, 25, and 27 that some use of the supplementary resistance heaters occurred at times when the compression system was operating between 90 and 100 percent of the time. This was probably caused either by a sudden advance of two degrees or more in the thermostat setting, or by a sudden cooling of the thermostat from an open door or similar occurrence. The thermostats in the dwellings at both bases were of the two-step heating type designed to energize the compression system on the first step and energize the supplementary resistance heaters (subject to the outdoor thermostat) on the second step whenever the room temperature fell 2 degrees below the first step setting. The heat pumps at both bases were equipped with outdoor thermostats to prevent use of supplementary resistance heaters when the outdoor temperature rose above the set point of the thermostat. At Seymour Johnson AFB one outdoor thermostat controlled all heaters, whereas at Columbus AFB two outdoor thermostats, set several degrees apart, were provided, each controlling half the installed heater elements.

6.4 Coefficient of Performance

The ratio of the heat delivery rate of the compression system of a heat pump to the power input to the system, expressed in the same units, is called the coefficient of performance. The coefficients of performance of the heat pumps in five sample houses at Seymour Johnson AFB and in four sample houses at Columbus AFB are reported in Tables 3 to 11, inclusive, and plotted in Figures 31 to 39, inclusive, for the range of outdoor temperature that occurred during the test periods. These coefficients were based on the measured power input to the compressor motor and two fan motors, and the heat delivery rate calculated from the measured air circulation rate and the temperature rise produced in the warmed air during steady operation or near the end of an operating cycle.

An inspection of Figs. 31 to 34 indicates that the coefficient of performance was nearly constant in house types A, B, and D, and increased only slightly in house type C at Seymour Johnson AFB for the outdoor temperature range from 20°F to 50°F. At an outdoor temperature of 20°F, the coefficients of performance ranged from about 1.4 in house type A to about 1.8 in house type D, with an average of 1.67 for the four systems. When tested in the laboratory, the coefficient of performance of the model heat pump used in house type C was 1.52 and the heating capacity was 14,300 Btu/hr at the same outdoor temperature but with the temperature at the inlet to the indoor coil controlled at 70°F.

Two curves for the coefficient of performance of the heat pump in house type E are plotted in Fig. 35, with the lower and upper curves representing the performance before and after repair and maintenance was performed on the unit, respectively. As described earlier in this report, a new capillary tube was installed in this unit and the system was recharged with refrigerant. As shown in Table 9 and Fig. 35, these repairs and maintenance operations increased the heating capacity about 50 percent and the coefficient of performance about 65 percent at an outdoor temperature of 35°F without an increase in power input. A laboratory test of the same model heat pump as that installed in the type E house indicated a coefficient of performance of 1.91 and a heating capacity of 24,000 Btu/hr at an outdoor temperature of 20°F and an indoor temperature of 70°F. There is no certainty, however, that all components in the two units of the same model number were identical.

Tables 8 to 10 and Figs. 36 to 38 indicate that the coefficients of performance of the unitary type heat pumps in three of the sample houses at Columbus AFB was about 2.0 at an outdoor temperature of 14°F and increased to 2.4, more or less, at an outdoor temperature of 45°F. Comparable values of the coefficient of performance were not obtained in the type A2D1 house because of the short periods of compressor operation required to maintain the house temperature. The effect on coefficient of performance of shifting from 3-cylinder to 2-cylinder operation in the outdoor temperature range between 30°F and 40°F is not clearly evident except in Fig. 37. In this instance, a coefficient of performance of 2.65 was observed for 3-cylinder operation at an outdoor temperature of 32.5°F, whereas coefficients of performance of 2.3 and 2.2 were observed for 2-cylinder operation in the outdoor temperature range from 32°F to 38°F.

The progressive shortening of the periods of compressor operation required to maintain the desired indoor temperature at higher outdoor temperatures may account for the relatively small change observed in the coefficient of performance with increasing outdoor temperature. That is, the coefficient of performance calculated from the heat delivery rate near the end of a short running period is probably lower than the steady state value, but on the other hand, it is higher than the average value realized for the whole of the short running period. These relationships can be illustrated by Figs. 40 and 41, which show the progressive change in the temperature rise of the air produced by the heat pumps after starting, as measured in the supply plenum and at the inlet to the indoor coil.

Figure 40 shows the pattern of temperature rise of the warmed air in the type D dwelling at Seymour Johnson AFB during two running periods each about 15 minutes in length in the lower curve, and during two running periods of 25 and 40 minutes' length in the upper curve. The longer running periods indicate that the temperature rise had reached a steady value, for practical purposes, in about 14 minutes after the blower started. The lower curves do not permit a definite evaluation because of the short running time, even though a steady temperature rise was probably being approached at the end of the running periods. At Seymour Johnson AFB, heat pump operation was initiated by the room thermostat on a decrease in room temperature; and the indoor blower was started by a pressure-activated control which sensed the condensing pressure in the indoor coil. It will be noted that a temperature decrease of 2 to 3 degrees occurred immediately after the blower started before the longer pattern of temperature rise occurred. The temperature rise decreased sharply at the end of the running period of the heat pump because the blower continued to run for a minute, more or less, after the compressor stopped.

Figure 41 shows the pattern of temperature rise of the warmed air in the type A3D1 dwelling at Columbus AFB during four running periods each about 10 to 13 minutes in length in the upper curve and during three running periods each 28 to 32 minutes in length in the lower curve. Both curves indicate that the temperature rise reached a steady value, for practical purposes, in 8 or 9 minutes after the blower started. In the dwellings at Columbus AFB the blower was started and stopped simultaneously with the compressor under the control of the room thermostat. Fig. 41 shows that the temperature in the supply plenum increased a few degrees after the blower and heat pump stopped because of the heat stored in the indoor coil, blower, and the sheet metal housing.

In Figure 42 the temperature rise of the warmed air is plotted as a percent of the steady state temperature rise in relation to the elapsed time after the start of blower operation in the type D and A3D1 dwellings. This figure indicates that the larger heat pump at Columbus AFB reached 90 percent of the steady state value of temperature rise in about 3 minutes, whereas the corresponding percentage was not attained by the smaller heat pump at Seymour Johnson until approximately 6 minutes after blower operation was initiated. If it is assumed that the electrical power input to the heat pumps was a constant from the instant of starting in these two installations, the transient coefficients of performance of the two units would be proportional to the percent of steady state temperature rise, since the heat delivered by the unit is directly proportional to the temperature rise of the warmed air. The average coefficient of performance of a heat pump during cyclic operation could be approximated by averaging the ordinates of curves like those in Figure 42 for the duration of the running period. Figs.

40 to 42, inclusive, indicate that coefficients of performance based on the temperature rise at the end of running periods of 15 minutes or more in the dwellings at Columbus AFB would not deviate from the steady state value by more than a percent or two.

Very little of the heat stored in the indoor unit and supply duct system of an attic installation like those in dwelling types A to D, inclusive, at Seymour Johnson AFB would be delivered by natural convection through the unit during the time the indoor blower was stopped. Since the supply grilles were at a level lower than the attic-mounted unit and the vertical portion of the return system was at room temperature, there would be virtually no motive force for natural circulation of air through the attic unit.

In the dwellings at Columbus AFB and the type E dwelling at Seymour Johnson AFB, the indoor coil was in a vertical housing a few feet above the floor level. In this type of installation enough chimney effect would be created in the vertical portion of the supply system to produce a low rate of natural circulation causing some of the heat stored in the system to be delivered at the supply grilles during the time the indoor blower was stopped.

Tha data taken during the field study did not provide a means for evaluating the amount of natural circulation of air through the systems when the indoor blower was stopped.

6.5 System Performance Factor

It will be noted in Tables 3 to 6, inclusive, and 8 to 11, inclusive, that the air temperature at the inlet to the cooling coil was lower than at the return air grille by amounts ranging from 3 to 7 degrees at the lowest outdoor temperature reported. This decrease in air temperature from the return grille to the coil inlet was caused principally by air leakage into the return system from the attic through openings described earlier in this report. The measurement of this air leakage is discussed in Section 6.6 of this report.

The unnecessary leakage of cold air from the attic into the return system represented a loss of useful heating capacity and a decrease in performance effectiveness of the system, since the return air had to be warmed from a lower temperature level because of the leakage. The total adverse effect of this air leakage would be related both to the percent running time of the blower and to the attic temperature. Since the attic temperature typically decreased and the percent running time increased as the outdoor temperature decreased, the cumulative penalty of the air leakage was compounded as the weather became colder.

A system performance factor was computed for each heat pump and air distribution system in which attic air leakage was observed, for comparison with the coefficient of performance of the heat pump itself. The system performance factor is defined as the ratio of the heat dissipation rate in the living space, computed from the difference between air temperatures at the supply plenum and the return air grille, to the heat equivalent of the power input to the compressor and fan motors. The system performance factors for four systems at Seymour Johnson AFB and four systems at Columbus AFB are shown in Tables 3 to 6 and Tables 8 to 11, respectively. These system performance factors are also plotted in Figs. 31 to 34 and Figs. 36 to 39 for graphical comparison with the coefficients of performance. The system performance factors were about 0.25 lower than the coefficients of performance at both housing projects for an outdoor temperature of about 45°F, whereas this disparity was 0.40 to 0.50 at the lowest outdoor temperatures experienced during the study at the two sites. The loss in useful heating capacity of the unit caused by the leakage of attic air into the return system was about 1000 Btu/hr at Seymour Johnson AFB and about 1500 Btu/hr at Columbus AFB for each degree F difference between the air temperature at the return grille and the inlet to the cooling coil. These losses could be avoided by a duct construction that prevented air leakage into the system from cold spaces.

Table 7 shows that there was less than 1 degree difference between the air temperature at the return grille and the inlet to the cooling coil in the type E house at Seymour Johnson AFB, in which the heat pump unit was located in a closet adjacent to the hall. Although there were some openings in the ceiling construction of this closet communicating with the attic, there was a negligible pressure difference across the louvered door and the grille through which the return air entered the utility closet, so little air leakage occurred from the attic.

6.6 Air Leakage in the Return Air System

The points at which air leakage occurred into the return system from the attics of the sample houses at both air bases have been described, and the effects of the air leakage on heating capacity and performance of the heat pump systems have been evaluated. The amount of air leakage was determined by two methods; namely, (a) by computation using the observed temperatures in the attic, at the return grille, and at the inlet to the cooling coil in conjunction with the total measured air flow rate, and (b) from air flow measurements made at one supply grille with the return grille and all the other supply grilles covered and sealed, together with static pressure measurements in the system. The air flow measurements were adjusted for the difference in the static pressures in the return system during normal operation and during operation with all but one supply grille covered and sealed.

The average leakage rates of attic air computed from the temperatures of the attic air, return air, and the mixture are summarized in Table 13 for the sample houses at each air base, whereas the leakage rates based on measured air flow values adjusted for static pressure changes in the return systems are shown in Table 14. The data in Table 13 indicate that the air leakage rates ranged from 45 cfm in the type E house to 180 in the type B house at Seymour Johnson AFB, corresponding to 3 percent and 19 percent of the total air delivery rates of the blowers, respectively. The air leakage rates at Columbus AFB ranged from 220 to 350 cfm or 15 to 25 percent of the total air delivery rates of the blowers. The leakage rates computed from the measured air delivery at one supply grille while all other grilles were sealed, as summarized in Table 14, are of the same order of magnitude as those obtained by computation from air temperatures. In Table 14 it is shown that a dirty filter or a dirty return grille increased the negative pressure in the return system about threefold and the air leakage from the attic by 70 to 80 percent for one dwelling at Seymour Johnson AFB and for two dwellings at Columbus AFB.

Tables 13 and 14 indicate that the leakage rates of attic air ranged from 0.5 to 1.2 air changes per hour in four of the five dwellings at Seymour Johnson AFB and from 1.3 to 2.5 air changes per hour in the five dwellings at Columbus AFB when the filters and return grilles were clean. While the high air intake rate from the attic would tend to pressurize the living space a small amount, it would not prevent normal infiltration into the living space under even moderately windy conditions. Thus, it is probable that the total volume of air leakage into the dwellings exceeded the rates indicated in Tables 13 and 14 by significant amounts.

7.0 Average Power Usage

Since the separate watthour meters connected to each of the major appliances in the sample houses were read every two hours during the test period, the amount of energy used by each appliance could be determined for selected periods of the day. For the purpose of analysis and comparison, the day was divided into three 8-hour periods: from midnight to 0800 hours, from 0800 to 1600 hours, and from 1600 to 2400 hours, approximately. The actual periods are staggered somewhat because the houses were visited consecutively by the observers during the test.

TABLE 13

COMPUTED ATTIC AIR LEAKAGE RATE INTO RETURN SYSTEM
BASED ON OBSERVED AIR TEMPERATURE

Dwelling Type	Street Address	Measured Total Air Circulation Rate cfm	House Volume ft^3	Air Leakage from Attic Rate cfm	Air Leakage from Attic Percent of Total Circulation	Air Leakage from Attic Air Changes
		Seymour Johnson AFB				
A	402 March Lane	926	7954	143	15	1.1
B	413 Craswell Lane	970	8995	180	19	1.2
C	217 Chanute Road	873	8138	123	14	0.9
D	215 Chanute Road	956	9316	83	9	0.5
E	301 Carswell Lane	1467	11190	45	3	0.2
		Columbus AFB				
A2D1	122 Vernon Ave.	1289	7433	277	23	2.2
A3D1	117 Caledonia Loop	1524	8234	227	15	1.7
A3D1	119 Caledonia Loop	1350	8234	336	25	2.5
03S1R	116 Florida Ave.	1439	10397	222	15	1.3
03S3	118 Florida Ave.	1384	10397	351	25	2.0

TABLE 14

ATTIC AIR LEAKAGE RATE INTO RETURN SYSTEM
BASED ON MEASURED VALUES, ADJUSTED FOR PRESSURE DIFFERENCE

Dwelling Type	Street Address	Total Air Circulation Rate	House Volume	Press.Diff.[a] House to Return System	Air Leakage from Attic		
					Rate	Percent of Total Circulation	Air Changes
		cfm	ft^3	In W.G.	cfm		
		Seymour Johnson AFB					
A	402 March Lane	926	7954	0.09	164	18	1.2
B	413 Carswell Lane	970	8995	0.07	178	18	1.2
C	217 Chanute Road	873	8138	0.08	211	24	1.2
D	215 Chanute Road	956	9316	0.07	107	11	0.7
D	215 Chanute Road	-	9316	0.20[b]	181	-	1.2
E	301 Carswell Lane	1467	11190	Negligible	Negligible	-	-
		Columbus AFB					
A2D1	122 Vernon Ave.	1289	7433	0.07	315	24	2.5
A3D1	117 Caledonia Loop	1524	8234	0.08	247	16	1.8
A3D1	119 Caledonia Loop	1350	8234	0.08	244	18	1.8
A3D1	119 Caledonia Loop	--	8234	0.25[c]	445	-	3.2
03S1R	116 Florida Ave.	1439	10397	0.09	242	17	1.4
03S1R	116 Florida Ave.	--	10397	0.25[c]	415	-	2.4
03S3	118 Florida Ave.	1384	10397	0.07	281	24	1.6

a/ During normal operation with all ducts open.
b/ Air filter at return grille dirty.
c/ Return louver very dirty.

7.1 Average Power Usage of Appliances

The average power used by each appliance during the three consecutive 8-hour periods and the daily average power for the five dwellings at each air base are shown in the bar graphs in Figures 43 and 44 for the duration of the test period. In the sample houses at Seymour Johnson AFB the total power and the incremental values for the water heater, dryer, and range were a maximum during the middle of the day, whereas the power used by the heat pump and strip heaters was a maximum during the 8-hour period from 0030 to 0830 hours and the miscellaneous power reached a maximum during the evening hours. In the sample houses at Columbus AFB the total power, and the incremental values for the heat pump, water heater, and dryer were a maximum during the middle of the day, whereas the power used by the miscellaneous devices was a maximum during the evening hours. The 24-hour average power usage was 3.96 KW for the five sample dwellings at Seymour Johnson AFB and 4.40 KW for the five sample dwellings at Columbus AFB.

The average daily energy usage by each component load and the sum for all component loads are shown in Table 15 for each of the five sample dwellings and as an average for all five dwellings at each of the two air bases. The percent of the total energy usage represented by each component is also shown for the five-dwelling average at each site. It will be noted that 52 to 55 percent of the total energy usage was used by the heat pump compressor, the supplementary resistance heaters, and the bathroom heater (bathroom heaters were installed only at Columbus AFB) which comprised the equipment installed specifically for house heating. The energy used for water heating ranged from 25 to 30 percent of the total, and the remainder of the energy (17 to 20 percent) was used for the ranges, clothes dryers, and miscellaneous devices.

Inspection of Table 15 indicates that the ratio of the largest to the smallest usage of energy in the individual dwellings at Seymour Johnson AFB was about 2 to 1 for all components of the load except for the clothes dryer, for which the ratio exceeded 3 to 1, and the supplementary resistance heaters with a ratio of 18 to 1. The energy used for the heat pump in the C type dwelling was the lowest by a considerable margin. The families in the B and C type dwellings were not at home for about a week during the test. In these two cases the dwellings continued to be heated, but the low values of energy usage recorded for cooking, water heating, clothes drying, and miscellaneous devices during these absences were not included in obtaining the average daily energy usage values in Table 15. Deletion of these values raised the average daily use for the whole house about 10 and 5 percent for the B and C dwellings, respectively. Absences of the other families during the test period were negligible. The average daily energy usage for the five sample dwellings was 95 KWH.

TABLE 15

AVERAGE DAILY ENERGY USAGE BY ELECTRICAL APPLIANCES
IN THE SAMPLE HOUSES, KWH

Appliance	Seymour Johnson AFB						
	Dwelling Type						Percent
	A	B	C	D	E	Avg	of Total
Heat Pump Compressor	42.52	56.13	33.42	42.48	60.59	47.03	49.4
Supp. Resistance Heaters	2.96	2.86	0.75	5.34	13.54	5.09	5.3
Water Heater	29.27	21.18	14.75	32.13	21.40	23.75	25.0
Range	1.59	4.76	1.76	3.75	3.91	3.15	3.3
Clothes Dryer	2.17	6.28	3.59	6.47	1.86	4.07	4.3
Miscellaneous Devices	8.35	13.36	8.30	16.11	14.23	12.07	12.7
Total	82.86	104.57	62.57	106.28	115.53	95.16	100.0

	Columbus AFB						
	Dwelling Type						Percent
	A2D1	A3D1	A3D1	O3S1R	O3S3	Avg	of Total
Heat Pump Compressor	34.34	49.40	29.11	64.13	59.38	47.27	44.8
Supp. Resistance Heaters	1.78	2.32	3.06	1.08	3.30	2.31	2.2
Bathroom Heater	4.28	0.72	16.78	5.20	1.46	5.69	5.4
Water Heater	27.21	36.99	41.59	24.28	30.11	32.04	30.3
Range	2.16	2.26	6.12	1.79	1.82	2.83	2.7
Clothes Dryer	2.77	5.04	5.83	2.92	3.27	3.97	3.8
Miscellaneous Devices	7.74	9.24	18.42	11.96	9.87	11.45	10.8
Total	80.28	105.97	120.91	111.36	109.21	105.56	100.0

Table 15 shows that the ratio of the largest to the smallest usage of energy in the individual dwellings at Columbus AFB was about 2 to 1 for the heat pump, the water heater, the clothes dryer, and the miscellaneous devices, and was about 3 to 1 for the supplementary resistance heaters and the cooking range. The energy usage for the bathroom heater was the most widely divergent of all appliances due to the high value observed in one of the type A3D1 dwellings. The occupant of the 03S3 dwelling was absent for about 3 weeks during the test period, so the use of energy for all appliances except the heat pump and supplementary resistance heaters was almost zero during this period. The daily averages shown in Table 15 for this dwelling cover the entire test period for the heat pump and supplementary resistance heaters, but cover only the 12 days when the house was occupied in the case of the other appliances. The average daily energy usage for the five sample dwellings was about 106 KWH.

It will be observed in Table 15 that the proportion of the total energy used in the various appliances was significantly different in one of the A3D1 type dwellings than for the other four dwellings. It appears that a significant part of the house heating was accomplished by the bathroom heater, range, and miscellaneous devices in this house. The energy use by these three appliances exceeded that used by the heat pump and supplementary resistance heaters by about 30 percent in this particular dwelling. This dwelling also had the highest average daily energy usage for all purposes among the five sample dwellings.

7.2 House Heating by Range, Water Heater, and Miscellaneous Devices

The energy used by an electric range, an electric water heater, and the miscellaneous electric devices in a house makes some contribution toward heating the house in any season of the year. This auxiliary heating reduces the load on the heating system in cold weather and may overheat the house in mild weather. In evaluating the contribution of these appliances to house heating during this field study, it was assumed that all of the energy input to the cooking range and to the miscellaneous devices such as electric lights, radio and television sets, refrigeration, electric iron, etc. assisted in warming the dwelling with very little time lag.

The jacket loss of the water heater would warm the house, if the heater were located in the living space, and a variable fraction of the heat in the warm water used for bathing, dishwashing, and laundry would be transferred to the air in the house as sensible or latent heat. At Seymour Johnson AFB the water heater was located inside the living space in four dwellings and outside the living space in the fifth, whereas at Columbus AFB it was located in the utility closet for the heat pump in two dwellings and in outside storage closets in the remaining three dwellings. Observations of the energy usage of the water heaters in a number of the sample dwellings during the night when no water was being drawn indicated that the jacket losses averaged about 150 watts. Apart from the jacket loss, it was assumed that 10 percent of the heat added to the water was effective in warming the dwelling.

It was assumed that the electric dryer contributed nothing toward heating the house. Although the clothes dryer had some jacket heat loss, it was equipped with a small blower which used room air to carry the water vapor and some sensible heat outside through a connected vent during the clothes-drying process. Such a blower would increase the infiltration of outdoor air when in operation which, in cold weather, would probably more than offset the jacket heat loss.

On the basis of the foregoing observations and assumptions, the contribution of the electric range, water heater, and miscellaneous devices to house heating was determined by equation (1) when the water heater was located inside the heated space, and by equation (2) when it was in a closet outside the heated space:

$$\text{kw-hr}_A = \text{kw-hr}_R + \text{kw-hr}_M + 0.1(\text{kw-hr}_W - 0.15) + 0.15 \qquad (1)$$

$$\text{kw-hr}_A = \text{kw-hr}_R + \text{kw-hr}_M + 0.1(\text{kw-hr}_W - 0.15) \qquad (2)$$

where kw - hr_R, kw - hr_M, and kw - hr_W are the metered electric energy use of the electric range, the miscellaneous devices, and the water heater, respectively, in kilowatt hours for the period of time under consideration; kw - hr_A is the computed contribution of these three appliances to house heating in kilowatt hours; and the constant 0.15 represents an average hourly observed jacket loss of the water heater in kilowatt hours.

Using equations (1) and (2) and the heat equivalent of electric energy, it was found that the range, water heater, and miscellaneous devices produced a heating effect ranging from 1500 Btu/hr during the eight-hour period beginning at midnight to about 3700 Btu/hr during the evening hours in the sample houses at Seymour Johnson AFB, whereas the corresponding range of values was from 1400 Btu/hr to 3400 Btu/hr at Columbus AFB. The daily average heating effect of these appliances was 2720 Btu/hr and 2510 Btu/hr, respectively, at the two sites. The data on the heat contribution of these appliances for the three eight-hour periods and the daily average are summarized in Table 16. It will be noted that the miscellaneous devices accounted for one-half to two-thirds of the total heating effect of this group of appliances.

7.3 Total Power and Total Power for Heating

The total power used for all purposes and the total power that contributed toward heating are shown in Figs. 45 to 47 as an average for the five sample houses at Seymour Johnson AFB, and in Figs. 48 to 50 as an average for the five sample houses at Columbus AFB. The power consumptions are plotted separately for the three eight-hour periods of the day in relation to outdoor temperature. The plotted values are scattered in all of these figures with the scatter being somewhat more pronounced for the values of the total power used for all appliances than for the power used for heating. This indicates that the power used for water heating and dryer functions was quite variable and was not appreciably dependent on outdoor temperature. The best-fitted curves for total power for all appliances and total power for heating were approximately parallel in each figure, with a slight upward curvature at lower outdoor temperatures.

The difference in power usages for heating and for all purposes was about 1 kw at both sites for the daytime and evening periods represented by Figures 46, 47, 49 and 50. As would be expected, this difference was considerably smaller, 1/5 to 1/3 kw, during the eight-hour period after midnight when there was little usage of the water heater or dryer. It will be noted that the power used for heating was on the order of 1 kw at outdoor temperatures in the range from 65°F to 70°F for the daytime and evening hours and somewhat lower during the hours after midnight. This suggests that the power used by appliances other than the heat pump would probably begin to overheat the dwellings at an outdoor temperature of 70°F, more or less.

TABLE 16

AVERAGE HOUSE HEATING ACCOMPLISHED
BY RANGE, WATER HEATER, AND MISCELLANEOUS DEVICES IN SAMPLE DWELLINGS,
BTU/HR

Appliance	Period of Day, Hours			
	Seymour Johnson AFB			
	0030-0830	0830-1630	1630-0030	All Day
Range	140	540	525	400
Miscellaneous Devices	840	1620	2450	1640
Water Heater	530	810	710	680
Total	1510	2970	3685	2720
	Columbus AFB			
	2300-0700	0700-1500	1500-2300	All Day
Range	120	620	510	420
Miscellaneous Devices	910	1420	2260	1530
Water Heater	370	670	630	560
Total	1400	2710	3400	2510

7.4 Correlation of Energy Input to the Heat Pump with Heating Degree-Days

The energy used by the heat pump in each sample dwelling, including the supplementary resistance heaters, was correlated with house size and severity of the weather by computing an energy-usage factor having the units kw-hr/degree-day (1000 ft^2). For this purpose, the daily degree-days were computed from the average of the hourly outdoor temperatures recorded at the weather station at each base and an indoor reference temperature of 65°F; and the inside floor areas of the dwellings were used. The daily values of the energy usage factor are plotted in Figs. 51 to 60 for the ten sample dwellings with degree-days per day as the independent variable. The average values for the entire test period at each site are summarized in Table 17.

Figs. 51 to 55 show a considerable variation in the value of the energy-usage factor in each of the sample dwellings at Seymour Johnson AFB for any selected value of degree-days. The energy-usage factor was significantly higher in mild weather, when the degree-days per day were in the range from 5 to 10, for three of the five sample dwellings. This could be the result of opening windows for ventilation or greater movement between indoors and outdoors in mild weather. However, no effort was made to observe these practices during the tests. At lower outdoor temperatures the average of the energy-usage factors remained relatively constant for the entire range of degree-days experienced during the test period. The energy-usage factors in the D and E type dwellings are shown to be much more variable than in the other three sample dwellings. As noted previously, replacement of the capillary tube and recharging with refrigerant was performed on the unit in the type E dwelling during the course of the tests, and the outdoor check valve in parallel with the capillary tube in the type D dwelling was erratic in its operation during a part of the time. These abnormal operating conditions probably accounted for the greater variability in energy usage in these two dwellings. Nearly all of the high values of the energy-usage factor observed in the E type dwelling occurred prior to repair of the heat pump.

Figs. 56 to 60 show that the energy-usage factor was also quite variable in the sample houses at Columbus AFB, but there was less indication of a sharp increase of this factor in mild weather than at the other site. Except for the type A3D1 dwelling at 119 Caledonia Loop, the average value of the energy-usage factor was approximately constant throughout the range of outdoor conditions experienced during the test. The energy-usage factor was significantly lower in this type A3D1 dwelling than for the four others at this site. Reference to the average daily energy usage by all appliances summarized in Table 15 and the discussion thereof, indicates that much greater use of the bathroom heater, range, and miscellaneous devices occurred in this dwelling. This undoubtedly reduced the need for heat pump operation and correspondingly reduced the energy-usage factor computed on the basis of energy consumption by the heat pump only.

TABLE 17

AVERAGE ENERGY USAGE FACTORS
FOR THE HEAT PUMPS IN TEN SAMPLE DWELLINGS

Dwelling Identification	Average Energy Usage Factor, KWH/deg-day(1000 ft^2)
	Seymour Johnson AFB
A	2.42
B	2.74
C	1.67
D	2.32
E	2.97
Avg. Outdoor Temp., °F	46
	Columbus AFB
A2D1	1.65
A3D1	1.90
A3D1	1.10
O3S1R	1.93
O3S3	1.88
Avg. Outdoor Temp., °F	39

Table 17 shows that the energy-usage factors in four of the five dwellings at Seymour Johnson AFB were higher than those for the dwellings at Columbus AFB. The following design factors, applicable to Seymour Johnson AFB, probably contributed to the higher energy-usage factor and lower coefficient of performance observed at this base.

(a) More use of the supplementary resistance heaters was required because the heat pumps were selected for a higher balance point temperature.

(b) There was some loss of heating capacity in the refrigerant lines connecting the indoor and outdoor units of the split systems.

(c) Very little of the heat absorbed by the attic ducts and attic-mounted heat pump units was brought into the living space by natural convection when the indoor blower stopped.

(d) The use of the bathroom heaters in the dwellings at Columbus AFB would contribute to a lower energy-usage factor for the heat pumps at this site.

8.0 Heating Requirements

The heating requirements of the sample dwellings were determined by calculation using conventional methods and by direct measurement using two different procedures. In one procedure, each sample dwelling was heated by the electric resistance heaters in the heat pump units during one or more cold days, without assistance from the compression system, to determine the heat requirement of the dwelling per unit indoor-outdoor temperature difference. The observed heat loss could then be extrapolated and corrected to the design outdoor conditions. In the second procedure the heat delivered to each dwelling by the heat pumps, operating normally, was determined from the measured air circulation rate and the integrated temperature rise of the warmed air during each running period; the heat delivered by other appliances was determined by either equation (1) or (2), discussed in Section 7.2 of this report; and the sensible heat input by the occupants was estimated on the basis of size of family and probable metabolic rate.

8.1 Calculated Heating Load of Dwellings

The heating load of each of the sample dwellings was calculated using the procedures described in the Guide of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. The areas of each of the exterior components of the dwellings and the heat transmission coefficients of each element of the structures were calculated mainly from the dimensions and description of materials shown in the as-built or architect's drawings. Some details of construction were obtained from the installation engineer's office at the site. The computed heat transmission coefficients for each type of exterior wall construction, for the windows, doors, ceilings, and floors, and the unit heat loss per linear foot of exposed floor edge are summarized in Table 18 for each site. The heat transmission factors were corrected for framing members in the construction.

The heat loss of each component of the ten sample dwellings was calculated using the areas summarized in Table 1 and the heat transmission factors summarized in Table 18. The design outdoor temperatures used for these calculations were the temperatures specified for the housing project designs; namely, 10°F at Columbus AFB and 20°F at Seymour Johnson AFB. The total computed transmission heat loss is shown as a subtotal for each dwelling in Table 19. Because of the excessive infiltration of air from the attic in most of the sample houses, the infiltration heating loads corresponding to 1, 1 1/2, and 2 air changes per hour of outdoor air are shown separately in Table 19.

Table 19 shows that the computed heat transmission loss of the four dwellings at Seymour Johnson AFB, each a part of a duplex structure, ranged from 21,600 to 24,800 Btu/hr, whereas that of the detached type E house was 37,700 Btu/hr at design outdoor temperature. The corresponding values for the total heating load with infiltration of outdoor air assumed to be one air change per hour are 28,800 to 32,900 Btu/hr for the duplex-type dwellings and 47,800 Btu/hr for the type E house. The air leakage rates from the attic, summarized in Tables 13 and 14, indicate that the total infiltration of outdoor air was probably one air change/hr or greater in four of the sample dwellings at Seymour Johnson AFB. However, air brought in from the attic was typically 13 to 20 degrees warmer than the outdoor air at design outdoor temperature, so the penalty of this attic air leakage would not be as great as indicated by the tabulated values for infiltration load in Table 19. The type E house did not have significant leakage from the attic.

Table 19 shows that the computed heat transmission loss of the duplex-type dwellings at Columbus AFB ranged from 23,800 to 26,400 Btu/hr, whereas, that for the detached officers' dwellings was about 36,400 Btu/hr at design outdoor temperatures. The corresponding values for the total heating load with infiltration of outdoor air assumed to be one air

TABLE 18

COMPUTED HEAT TRANSMISSION FACTORS
FOR COMPONENTS OF SAMPLE HOUSES

Building Component	Heat Transmission Factor, Btu/hr(ft^2)(°F)
Seymour Johnson AFB	
Exterior Walls	
Brick Veneer Finish	0.073
Grooved Plywood Finish	0.071
Cavity Brick	0.380
Ceiling (Ventilated Attic)	0.047
Windows, Single	1.24
Doors, Solid Core	0.40
Floor Edge, Insulated	35[a]
Columbus AFB	
Exterior Walls	
Brick Veneer Finish	0.088
Exterior Plywood Finish	0.092
Shake Siding Finish	0.093
Vertical V-joint Siding	0.093
Ceiling and Roof Combined (Unventilated Attic)	0.090
Windows, Single	1.24
Doors, Solid Core	0.40
Floor Edge, Insulated	35[a]
Floor Edge, Uninsulated	50[a]

[a] Units of floor factor: Btu/hr (linear foot of cold floor edge)

TABLE 19

CALCULATED DESIGN HEAT LOSS RATES
OF SAMPLE DWELLINGS

Building Component	Heat Loss Rate, Btu/hr				
	Dwelling Type, Seymour Johnson AFB				
	A	B	C	D	E
Exterior Walls	2530	3250	2570	2870	8710
Windows	11900	13080	11900	13080	18040
Doors	800	800	800	800	1160
Ceiling	2330	2640	2390	2730	3070
Floor	4060	5010	4130	4550	6760
Total Transmission Load	21620	24780	21790	24030	37740
Infiltration Load, 1 air change/hr	7160	8100	7320	8380	10070
1½ " " "	10740	12140	10990	12580	15110
2 " " "	14320	16190	14650	16770	20140

Building Component	Dwelling Type, Columbus AFB			
	A2D1	A3D1	03S1R	03S3
Exterior Walls	3420	3670	5890	6000
Windows	9150	10860	14430	14430
Doors	1340	1340	1340	1340
Ceiling and Roof	5010	5550	7010	7010
Floor	4830	4930	7820	7430
Total Transmission Load	23750	26350	36490	36210
Infiltration Load, 1 air change/hr	8030	8890	11230	11230
1½ " " "	12040	13340	16840	16840
2 " " "	16060	17790	22460	22460

change per hour are 31,800 to 35,200 Btu/hr for the duplex-type dwellings and about 47,600 Btu/hr for the detached houses, types 03S1R and 03S3. The air leakage rates from the attic, summarized in Tables 13 and 14, indicate that the total infiltration rate of outdoor air probably exceeded two air changes per hour in several of the sample dwellings at Columbus AFB. In the coldest weather experienced during the test period, with snow on the roof, the attic air temperature was 25 to 30 degrees warmer than the outdoor air. However, in milder weather, with outdoor temperature near freezing but without snow on the roof; the attic air temperature was only 5 to 10 degrees warmer than the outdoor air, even though the gable louvers were sealed. Thus the increment of heating load caused by air leakage from the attic might be either larger or smaller than the values shown in Table 19 for one air change per hour of outdoor air, depending on the attic temperature.

8.2 Heat Loss Calibration by Resistance Heating

Each of the ten sample dwellings was heated solely by electric resistance heating for one or more cold days to evaluate the heat loss per degree indoor-outdoor temperature difference. The supplementary resistance heaters in the heat pump were used for this purpose and the indoor blower was operated continuously in some cases, and intermittently in phase with the heaters in other cases. The data taken during the night between the hours of 2200 and 0800 were used for analysis to avoid the effects of solar radiation, the more variable daytime outdoor temperature, and the highly variable appliance usage by the occupants.

The heat contribution of the water heater, range, miscellaneous appliances, and occupants was added to the metered energy use by the supplementary resistance heaters to determine the total heat supplied to the dwelling. The indoor-outdoor temperature difference was based on the temperature observed at the weather station of the air base and the indoor temperature measured at the thermostat. This latter temperature differed from the return air temperature in some cases, but was considered to be more representative of the temperature which determined the overall heat loss of the structure.

The data observed during the calibration tests with electric resistance heating are summarized in Tables 20 and 21 for the sample dwellings at Seymour Johnson AFB and Columbus AFB, respectively. In most instances the sample dwellings were heated by resistance heating for two or more days, with variations in outdoor temperature and wind velocity on different days. All valid tests conducted in each dwelling are summarized in Tables 20 and 21.

TABLE 20

HEAT LOSS CALIBRATION WITH RESISTANCE HEATING
SEYMOUR JOHNSON AFB, DECEMBER 1959 - JANUARY 1960

Item		Dwelling Type							
		A	A	B	B	C	D	E	E
Hours of Test		0030-0830	0030-0830	0030-0830	0030-0830	0030-0830	2400-0800	2400-0800	2400-0800
Duration of Test	hr	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Average Indoor Temperature,	°F	76.0	76.0	72.8	73.4	72.5	74.0	70.5	70.5
Average Outdoor Temperature,	°F	38.6	40.0	38.6	40.0	38.3	35.6	38.6	40.0
Average Temperature Difference,	°F	37.4	36.0	34.2	33.4	34.2	38.4	31.9	30.5
Average Wind Velocity,	mph	4.9	Calm	4.9	Calm	1.4	4.4	5.0	Calm
Average Attic Temperature,	°F	52.8	53.0	51.4	53.8	46.0	46.3	52.0	53.7
Observed Blower Operating Time,	%	100	100	100	100	61	100	100	100
Observed Heat Input Rate,	Btu/hr								
Resistance Heaters		16,810	14,210	13,630	13,360	11,430	19,080	20,060	19,000
Other Sources		1,850	1,510	4,170	2,420	2,290	1,430	1,930	2,390
Total		18,660	15,720	17,800	15,780	13,720	20,510	21,990	21,390
Observed Heat Transmission Factor,	Btu/hr(°F)	499	437	520	472	402	534	689	701
Extrapolation of Observed Heat Input to Design Temp. Difference,	Btu/hr	24,950	21,820	26,200	23,620	20,060	26,710	34,450	35,060
Corrections to Extrapolated Heat Loss									
Attic Air Leakage,	Btu/hr	100	440	340	740	2,530	-310	---	---
Window Heat Transmission, 15 mph wind,	Btu/hr	2,070	4,200	2,210	4,600	3,400	2,400	2,930	6,470
Corrected Heat Loss Rate at Design Conditions,	Btu/hr	27,120	26,460	28,750	28,960	25,990	28,800	37,380	41,530

TABLE 21

HEAT LOSS CALIBRATION WITH RESISTANCE HEATING
COLUMBUS AFB, FEBRUARY 1960

Item		Dwelling Type										
		A2D1	A2D1	A3D1	A3D1	A3D1	A3D1	O3S1R	O3S1R	O3S3	O3S3	O3S3
Hours of Test		2200-0600	2200-0600	2210-0610	2210-0610	2220-0620	2220-0620	2335-0735	2335-0735	2345-0745	2345-0745	2345-0745
Duration of Test	hr	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Average Indoor Temperature,	°F	77.3	78.0	79.7	80.0	82.7	82.9	77.4	78.2	76.0	76.0	75.6
Average Outdoor Temperature,	°F	17.7	34.7	16.7	34.7	17.7	34.7	16.7	34.3	18.3	16.8	34.3
Average Temp. Difference,	°F	59.6	43.3	62.0	45.3	65.0	48.2	60.7	43.9	57.7	59.2	41.3
Average Wind Velocity,	mph	Calm	5.2	Calm	5.2	Calm	5.2	Calm	5.2	Calm	3.8	5.5
Average Attic Temperature,	°F	44.5	48.5	42.8	47.7	45.7	49.1	46.2	48.0	47.8	47.8	50.0
Observed Blower Operating Time,	%	53.0	40.1	53.4	42.8	62.4	49.4	71.3	56.9	100	100	64
Observed Heat Input Rate	Btu/hr											
Resistance Heaters		19,630	14,730	20,910	16,810	23,510	18,390	29,180	23,310	36,840	34,430	25,730
Other Sources		1,310	1,610	3,740	2,980	5,350	4,290	2,380	2,380	1,070	900	1,330
Total		20,940	16,340	24,650	19,790	28,860	22,680	31,560	26,190	37,910	35,330	27,060
Observed Heat Transmission Factor,	Btu/hr(°F)	351	381	397	437	444	471	520	596	657	597	655
Extrapolation of Observed Heat Input to Design Temperature Difference,	Btu/hr	21,080	22,850	23,850	26,200	26,620	28,220	31,200	35,770	39,430	35,800	39,300
Corrections to Extrapolated Heat Loss												
Attic Air Leakage	Btu/hr	6,980	8,170	6,680	6,450	6,400	6,630	7,090	5,470	8,660	8,430	8,690
Window Heat Transmission at 15 mph wind,	Btu/hr	3,220	1,460	3,820	1,740	3,820	1,740	5,080	2,310	5,080	2,910	2,190
Corrected Heat Loss Rate at Design Conditions,	Btu/hr	31,300	32,480	34,350	34,390	36,840	36,590	43,370	43,550	53,170	47,140	50,900

In each of these tables the observed indoor and outdoor conditions during the tests were first summarized, followed by a summation of the observed heat input rates into the dwellings from all sources. An observed heat transmission factor with the units Btu/hr(°F) was computed from the total heat input rate and the observed indoor-outdoor temperature. These heat transmission factors were then used to compute the heat requirements of the dwellings at the design indoor-outdoor temperature difference of 50°F at Seymour Johnson AFB and 60°F at Columbus AFB by an extrapolation or interpolation procedure.

It will be noted that the average wind velocity during the calibration tests ranged from calm to 5.5 mph at the two bases. Thus, a heat requirement at design indoor-outdoor temperature difference based on heat transmission factors observed at these low wind velocities would probably not be representative of the design heat loss with a 15 mph wind. Two corrections were made to these computed heat requirements: one to account for the additional heat transmission through the windows caused by a 15 mph wind and the other to account for the increased intake of attic air caused by the higher percentage of blower operation at design conditions. The corrections for window heat transmission were made in accordance with the values of the coefficients for single glass at various wind velocities tabulated in the ASHRAE Guide. The corrections for air leakage from the attic were based on the increase in operating time of the indoor blower and the change in the temperature difference between the attic and the living space at design outdoor conditions. No corrections were made to the heat transmission of walls, floor, and ceiling since an increase in wind velocity to 15 mph would cause only about one percent increase in the heat transmission factors of these elements of the structures. The corrected heat loss rate at design conditions cited at the bottom of Tables 20 and 21 incorporate the two corrections described above and represent the best estimate of the design heat loss that can reasonably be derived from the calibration tests with the resistance heaters.

Tables 20 and 21 show that data were taken in eight of the ten sample dwellings under calm outdoor conditions and also with a wind velocity of about 5 mph. In six of these dwellings the heat transmission factor in Btu/hr per degree indoor-outdoor temperature difference was higher for the test with a 5 mph wind than for the test with calm weather, by amounts ranging from 6 to 15 percent. When the corrections were made in these six dwellings for the increased heat transmission through the windows and the increased attic air leakage at design outdoor conditions as described above, the corrected heat loss values for the two conditions of wind differed by amounts ranging from 0.1 to 3.7 percent. In the other two houses in which duplicate tests were made, the type E house at Seymour Johnson AFB and the type 03S3 house at Columbus AFB, the disparity between the corrected heat loss rates for duplicate tests was 11 and 4 percent, respectively. In the type E

house the thermostat was responsive only to the return air temperature from the bedroom section of the house. In this house the air temperature at the thermostat was several degrees colder than the air at the return grille, whereas the reverse relationship existed in the other dwellings at Seymour Johnson AFB. It is not known whether the different relation between thermostat temperature and return air temperature in the E type house had any bearing on the greater inconsistency of test results described above.

A comparison of the corrected heat loss rates at design conditions in Table 20 with the computed heat loss rates in Table 19 for the dwellings at Seymour Johnson AFB shows that the values derived from the calibration tests exceeded the computed total heat transmission loads in each case. However, they were less than the sum of the computed total heat transmission load and the infiltration load corresponding to one air change per hour of outdoor air, by amounts ranging from 2000 Btu/hr in the type A dwelling to 8350 Btu/hr in the type E house. This latter disparity suggests that the total heating load caused by infiltration of air by all avenues of entry was less than the equivalent of one air change per hour of air at outdoor temperature.

A comparison of the corrected heat loss rates at design conditions in Table 21 with the computed heat loss rates in Table 19 for the dwellings at Columbus AFB shows that the values derived from the calibration tests also exceeded the computed total heat transmission loads in each case. However, they were less than the sum of the computed total heat transmission load and the infiltration load corresponding to one air change per hour of outdoor air in the type O3S1R dwelling and one of the type A3D1 dwellings, and greater than this sum in the other three dwellings. These comparisons suggest that the total heating load caused by infiltration of air by all avenues of entry was somewhat less in some dwellings and somewhat more in others than the equivalent of one air change per hour of air at outdoor temperature.

These comparisons of measured and computed loads indicate that the intake of attic air may have supplanted normal infiltration to a considerable extent. The intake of attic air, even though excessive in amount, may not have augmented the heating load as much as might have been expected because it was preheated appreciably by the heat transfer through the ceiling.

8.3 Heat Supplied to Dwellings during Normal Operation

The heat supplied to each of the sample dwellings during normal operation of the heating system was determined for a range of outdoor temperature. These determinations were based on the heat delivered by the heat pump, and the calculated contribution toward heating by other appliances and by the sensible heat output of the occupants. The hours between midnight and 0800 hours were used for this analysis to avoid the variable effects of solar heating and the greater use of other appliances by the occupants during the day. Operating data which appeared to be distorted by setback of the thermostat at the time of retiring were discarded. The heat supplied by the heat pump during the periods of analysis was calculated from the air delivery rate of the blower, the total blower operating time, and the integrated temperature rise of the warmed air between the return grille in the house and the supply plenum for each operating period of the blower. This method of calculation excluded any heat that might have been supplied to the dwelling by natural convection when the blower was stopped and also excluded the heat used to warm the air brought into the system from the attic. As noted earlier in this report, natural convection probably supplied virtually no heat to the dwellings in which the heat pump and duct system was installed in the attic.

The quantities of heat supplied by the heat pump alone and from all sources are shown in Figs. 61 to 65 for the sample dwellings at Seymour Johnson AFB, and in Figs. 66 to 70 for the sample dwellings at Columbus AFB for a range of indoor-outdoor temperature difference. The corresponding values of heat input during the calibration tests with resistance heaters are superimposed on these graphs for comparison. In each case the plotted values of heat supplied to the dwelling does not include that required to warm the leakage air from the attic.

In most cases a straight line was the best representation of the relation between the heat supplied to the dwellings and the indoor-outdoor temperature difference within the range of values available. Exceptions will be noted in Figs. 64, 69 and 70 in which the slopes of the curves decreased somewhat for mild weather. Although it was not verified by actual observation, the most probable explanation for this condition is that the occupants opened windows more frequently at night in mild weather. Occupants were requested to leave windows closed during the tests, and did so generally, but not in all cases.

In nearly every graph there are a few days for which the calculated heat supply rate deviates appreciably from the straight line relationship. In some cases high values can be attributed to a higher-than-average wind velocity, but there was not full correlation between these factors. In some dwellings, such as those at 122 Vernon Avenue and 119 Caledonia Loop at Columbus AFB, only a few useful data were

obtained because the occupants regularly set their thermostats back several degrees before retiring. Under these conditions the heat loss from the building did not approach a steady state for a number of hours after setback of the thermostat, and in many cases, significantly less heat was required during the period of hours selected for this analysis. Additional heat was required to restore the interior temperature when the thermostat was reset to normal temperatures. This heating requirement has not been analyzed.

In most cases the heat requirements determined during the calibration tests with resistance heating agreed well with the values determined for normal operation of the heating system at the same indoor-outdoor temperature difference as illustrated in Figs. 63-68, inclusive. In Figs. 69 and 70 the heat requirement determined by electric resistance heating was appreciably lower than the observed values during normal heating at the design temperature difference of 60°F. However, as noted previously, there was a heavy layer of snow on the roofs and higher-than-anticipated attic temperatures in the dwellings at Columbus AFB during the period of calibration with the resistance heaters at low outdoor temperature. This may account for the lower heat requirement observed in these two cases during the calibration tests.

Table 22 provides a comparison of the heat requirements of the sample dwellings by various methods of evaluation. The first three columns of the table list the computed heat loss of the dwellings with a 15-mph wind, but without infiltration; the observed heat requirements by electric resistance calibration and under normal operation of the heating system but not including the effect of attic air leakage in either case. The values in the second and third columns are directly comparable except for variations in wind velocity and unknown variations in living habits such as the opening of windows for ventilation. The calculated values in the first column are not directly comparable with the values in the second and third columns in that the calculated values of heat loss are computed from coefficients based on a 15-mph wind, and include no allowance for infiltration whereas the values in the second and third columns take into account existing wind velocities and whatever normal infiltration occurred in the dwellings below the ceiling level at the time the observations were taken. As shown in Tables 20 and 21, the window heat transmission for a 15-mph wind velocity exceeded that for the wind velocity which prevailed during the calibration tests by amounts ranging from 1460 to 6470 Btu/hr in different tests and in different dwellings. It will be noted in Table 22 that the calculated values of heat loss in the first column exceeded the observed values in the second and third columns by amounts in about the same range of magnitude.

TABLE 22

COMPARISON OF HEAT REQUIREMENTS OF SAMPLE DWELLINGS
BY VARIOUS METHODS OF EVALUATION

Dwelling Designation	Heating Requirement at Design Indoor-Outdoor Temperature Difference[c]				
	Calculated Heat Loss with 15-mph Wind, without Infiltration	Electric Resistance Calibration, without Attic Leakage	Observed Heat Requirement, Normal Operation, without Attic Leakage	Calculated Heat Loss with 15-mph Wind and One Air Change Infiltration	Electric Resistance Calibration, Corrected for Attic Leakage and 15-mph Wind
	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr
			Seymour Johnson AFB		
A	21,620	17,860	14,000	28,780	26,790
B	24,780	18,980	23,500	32,880	28,860
C	21,790	15,300	16,800	29,110	25,990
D	24,030	23,250	24,200	32,410	28,800
E	37,740	34,760	37,500	47,810	39,460
			Columbus AFB		
A2D1	23,750	16,890	17,000	31,780	31,890
A3D1[a]	26,350	19,500	24,700	35,240	34,370
A3D1[b]	26,350	22,380	21,000	35,240	36,720
03S1R	36,490	29,290	33,700	47,720	43,460
03S3	36,210	29,220	31,500	47,440	50,400

[a]Dwelling at 117 Caledonia Loop, Columbus AFB
[b]Dwelling at 119 Caledonia Loop, Columbus AFB
[c]50 deg. F for Seymour Johnson AFB; 60 deg. F for Columbus AFB

The fourth and fifth columns in Table 22 provide a comparison of the calculated heat loss for a 15-mph wind and an infiltration of one air change per hour at outdoor temperature with the observed value obtained by electric resistance calibration after correcting the latter for a 15-mph wind and the increased attic air leakage at design conditions. The values in these latter two columns are directly comparable if the attic air leakage is considered to be a part of the overall infiltration. It will be noted that the calculated heat losses at design conditions in the fourth column exceeded the observed values (corrected) in the fifth column for the dwellings at Seymour Johnson AFB, by amounts ranging from 2000 to 8350 Btu/hr. At Columbus AFB the computed values ranged from 4250 Btu/hr higher to 2720 Btu/hr lower than the corrected values derived from electric resistance calibration. It is evident from the data in Tables 20 to 22 that the observed heat requirements of the sample dwellings under the most severe outdoor and indoor conditions that existed during the month-long test periods were considerably below the calculated heat loss of the structures at design outdoor conditions of temperature and wind. The significance of a 15-mph wind on the heat transmission rate of windows and on air leakage is evident from these comparisons.

8.4 Daily Average Energy Usage Rate

The hourly energy usage rate, averaged on a daily basis, was determined for each day of the test period for each of the sample dwellings. These average energy usage rates for the heat pump by itself and for all components contributing toward heating the dwellings are plotted for a range of outdoor temperature in Figs. 71 to 80, inclusive. The energy usage rates are plotted in units of Btu/hr to facilitate comparison with similar graphs in Figs. 60 to 70 showing the heat supplied to the dwellings. Except for the difference in the time period used for averaging the data in these two groups of graphs, the ratio of the heat supplied to a given dwelling to the energy usage rate expressed in the same units represents what might be termed a performance factor for the house. Such a performance factor includes all appliances that contributed to heating as a part of the heating system, even though the primary purpose for a part of the energy use was for some other function such as cooking, lighting, etc.

It will be noted that the energy usage curves in Figs. 71 to 80 all became steeper as the outdoor temperature decreased. This trend was to be expected since the coefficient of performance of the compression system decreased with outdoor temperature, and in the case of the dwellings at Seymour Johnson AFB a correspondingly higher percentage of supplementary resistance heating was required.

Except for the type D house at Seymour Johnson AFB in which poor performance of the heat pump was experienced for part of the test period, the energy usage curves indicate that the energy usage rate of the heat pump would become zero for outdoor temperatures in the range from 60°F to 70°F. Other appliances accounted for an energy usage rate for heating in the range from 1000 to 3000 Btu/hr, except for the type A3D1 dwelling at 119 Caledonia Loop, which averaged about 5500 Btu/hr. Reference to Table 15 indicates that this latter dwelling was the one with unusually high energy consumption for the bathroom heater, the miscellaneous devices, the cooking range, and the water heater and a correspondingly low energy usage for the heat pump.

It should be noted that Figs. 71 to 80 automatically take into account the effect of solar heating during the day; unusual infiltration rates caused by exhaust fans, open windows, and attic leakage; overheating caused by the miscellaneous appliances in mild weather; night setback of the thermostat; and any other practices of a given family or factors of a given dwelling that affected the magnitude of the heat requirements. That is, the data represent the heat requirements of the structure on an "as-used" basis for the duration of the test.

8.5 Comparison of Average Electric Energy Use in Sample Dwellings with That in Larger Groups

The average energy use for all purposes in the five sample dwellings was compared for a 31-day period with the metered energy use in other groups of dwellings at the same sites. At Seymour Johnson AFB such a comparison was possible with groups of 8, 11, 58, 225, and 1500 dwellings, the latter figure comprising the entire housing project. At Columbus AFB the comparison could be made between the five sample dwellings and the entire housing project, comprising 480 dwellings. At the former site the metering periods for the several groups of dwellings were identical, whereas at the latter site the metering periods for the sample dwellings and the entire project were staggered by one day.

The average energy use data are summarized in Table 23. The average energy use in the five sample dwellings at Seymour Johnson AFB was 95.3% of the average for the entire housing project, whereas the average energy use for the group of 8 dwellings was as low as 83% and that of the group of 225 dwellings as high as 102% of the average for the entire project. At Columbus AFB the average energy use for the five sample dwellings was 99.1% of the average for the entire housing project comprising 480 dwellings.

TABLE 23

COMPARISON OF AVERAGE ENERGY USE IN SAMPLE DWELLINGS WITH THAT IN LARGER GROUPS OF DWELLINGS

No. of Dwellings	Period of Analysis	Average Energy Use for 31-Day Period, for Entire Dwelling, Kwh
		Seymour Johnson AFB
5 (Sample Dwellings)	12/22/59 to 1/22/60	2867
8	"	2500
11	"	2771
58	"	2917
225	"	3072
1500 (Entire Project)	"	3009
		Columbus AFB
5 (Sample Dwellings)	2/23/60 to 3/23/60	2889
480 (Entire Project)	2/22/60 to 3/22/60	2916

9.0 Other Observations

The heat pumps at Columbus AFB produced a higher noise level in the dwellings than those at Seymour Johnson AFB in two ways. The air noise at the discharge grilles was higher, and the mechanical sounds caused by starting and stopping of the compressor and outdoor fan were transmitted into the house structure more noticeably from the indoor location of the units at Columbus AFB than from the outdoor location of this component at Seymour Johnson AFB.

Outdoor thermostats to limit use of supplementary resistance heating for outdoor temperatures above approximately 30°F were installed and in working order in the heat pumps in the five sample dwellings at Columbus AFB. There were two such thermostats, each controlling half of the supplementary heaters and set to operate a few degrees apart. The heat pumps in five sample dwellings at Seymour Johnson were each equipped with a single such thermostat, either shunted or set to permit operation of the supplementary heaters at outdoor temperatures considerably above the balance point for these houses. At both sites the supplementary resistance heaters were not energized unless also called for by the indoor thermostat or the defrost control.

The indoor thermostats in the five sample dwellings at Columbus AFB were located either in the living room or in the hall area adjacent to the main air return to the utility closet containing the heat pump. The indoor thermostats in four of the sample dwellings at Seymour Johnson AFB were installed in the hall area adjacent to the main air return and filter. In the type E house, the thermostat was not responsive to the living-dining room air temperature, but was influenced primarily by air temperatures in the front entrance hall and by air returning from the bedrooms.

In four of the sample dwellings at Columbus AFB, the entire heat pump was readily accessible for service. In the type A2D1 dwelling, the closet containing the heat pump could be entered only by removing an access panel in the clothes closet in the master bedroom, and unit replacement required removal of a section of the living room wall. The outdoor units of the heat pumps at Seymour Johnson AFB were readily accessible for servicing. In four of the sample dwellings servicing of the indoor units was handicapped by the limited access area in the attic. In the type E dwelling, the indoor unit was in a first floor utility closet and readily accessible.

The main return air louver from the hall to the utility closet in the five sample dwellings at Columbus AFB was designed to eliminate line-of-sight openings and the fin spacing was close enough so dust could accumulate on the louver. Enough dust had collected on the return louver in one dwelling prior to the test to increase the pressure

drop across the louver from 0.08 to 0.20 in. W.G. under normal operation of the heat pump, thus increasing the amount of leakage air drawn from the attic. As described earlier in the report, air filters in four of the sample dwellings at Seymour Johnson AFB produced similar effects on attic air leakage as the filters became loaded with dust.

Control of indoor fan operation during heating was different in the two types of heat pumps. At Columbus AFB the indoor fan, under automatic operation, started and stopped simultaneously with the compressor under control of the indoor thermostat, and continued to run during defrost cycles. At least a part of the supplementary heaters were energized during defrost cycles in these units. At Seymour Johnson AFB, the indoor fan, under automatic control, started and stopped in response to a pressure switch connected into the vapor refrigerant line of the indoor coil, and did not run during defrost cycles unless the indoor thermostat called for supplementary heating.

No repairs other than minor adjustments were required for the heat pumps in the five sample dwellings at Columbus AFB during the test period covered by this report. Some repairs were required at Seymour Johnson AFB. In addition to minor adjustments and addition of refrigerant to some or all of the heat pump systems in the five sample houses at Seymour Johnson AFB, the following maintenance and repair functions were required:

1. The upstream faces of the indoor coils were cleaned in two systems.
2. The outdoor restrictor tube and check valve and the outdoor fan wheel and fan bearings were replaced in one system.
3. The outdoor restrictor tube and check valve were replaced in a second system.

The compressors in the heat pumps in the five sample dwellings at Columbus AFB were of 3-cylinder construction, the third cylinder used to increase heating capacity for outdoor temperatures lower than 30° to 40°F and unloaded at other conditions. Two-cylinder compressors were used in the test units at Seymour Johnson AFB. Overloading due to high discharge pressure during mild weather heating was prevented at Columbus AFB by unloading the third cylinder at high outdoor air temperatures, and at Seymour Johnson AFB by stopping the outdoor fan in response to a pressure switch sensing the refrigerant pressure in the indoor coil. Each system functioned satisfactorily during the two test periods.

Defrost cycles were initiated for the heat pumps at Columbus AFB by a pressure switch sensing the pressure drop in the air flow through the outdoor coil, and at Seymour Johnson AFB by a temperature switch sensing the temperature differential between the refrigerant in the outdoor coil and the air flowing through the outdoor coil. One defrost switch required adjustment at Seymour Johnson AFB. Otherwise, the two systems performed satisfactorily in the five sample dwellings at each site for the respective test periods.

10.0 Discussion and Conclusions

This study of the heating performance of the air-to-air heat pumps in 5 sample dwellings at Seymour Johnson AFB and an equal number at Columbus AFB provides useful information on the performance characteristics of the heat pump itself, on the heat distribution system, on the heat requirements of the dwellings at design conditions, on energy usage for all electric appliances, and on the effect of the living habits of the occupants on the heat requirements of the dwellings. Whereas there was malfunctioning of the heat pumps in a few sample dwellings during the test period which required maintenance and repair, it was not the purpose of this investigation to make any systematic record or study of the maintenance requirements in the sample dwellings or the housing project in general.

Some of the principal conclusions indicated by this study may be summarized as follows:

1. The steady state heating capacity of the air-to-air heat pumps increased approximately linearly with increasing outdoor temperature. The observed steady state heating capacities of the compression systems in the heat pumps at outdoor temperatures near design conditions, as reported in Tables 3 to 11, indicated that the compression systems would provide from 51 to 82 percent of the heat requirement of the sample dwellings at Seymour Johnson AFB and from 99 to 116 percent of the heat requirements of the sample dwellings at Columbus AFB at design outdoor temperatures and wind velocities based on the calibration tests with resistance heaters as summarized in Table 22. In each case the supplementary resistance heaters provided considerably more than the required amount of additional heating capacity. Changing from 3-cylinder to 2-cylinder operation at an outdoor temperature between 30°F and 40°F reduced the heating capacity of the heat pumps at Columbus AFB by 5500 to 7500 Btu/hr, approximately 10 to 15 percent.

2. The highest outdoor temperatures requiring heat pump operation ranged from 58.5°F to 65°F in the various sample dwellings based on conditions prevailing during the night. For the wind conditions that occurred during the test periods, the balance point temperature ranged from about 28°F to 31°F in the five sample houses at Seymour Johnson AFB and from -3°F to 15°F for the three sample houses at Columbus AFB in which satisfactory data could be obtained. Obviously, the balance point would vary some with wind velocity, use of miscellaneous appliances in the house, and living habits.

3. The coefficients of performance of the heat pumps at Seymour Johnson AFB ranged from about 1.4 to 1.8 in dwellings A, B, C and D, and was about 2.4 in the type E house, after repair of the unit, for an outdoor temperature of 20°F. The coefficients of performance of the heat pumps in three of the sample dwellings at Columbus AFB were about 2.0 at an outdoor temperature of 14°F and increased to 2.4,

more or less, at an outdoor temperature of 45°F. These coefficients were based on approximately steady state operating conditions, and do not include the warmup period for the supply air at the beginning of each operating cycle.

4. The air circulation rates through the indoor coil of the heat pump units ranged from 873 cfm to 970 cfm in dwelling types A, B, C, and D and it was 1467 cfm in house type E at Seymour Johnson AFB. The air circulation rates in the 03S1R, 03S3, and two A3D1 dwellings at Columbus AFB ranged from 1350 cfm to 1524 cfm. These values were based on the temperature rise produced in the air by a measured amount of energy dissipation in the supplementary resistance heaters and in the indoor fan motor. A significant amount of attic air was drawn into the return duct system of the A to D type dwellings at Seymour Johnson AFB because the return duct and its frame were not well-fitted into the ceiling of the closet that was used as a return air passage; and in all of the dwellings at Columbus AFB because the opening in the utility closet wall through which the main supply duct entered the attic space was considerably larger than the duct. The attic air leakage ranged from 9 to 19 percent of the total air circulation rate in the four dwellings at Seymour Johnson AFB and from 15 to 25 percent in the five dwellings at Columbus AFB.

5. A system performance factor was computed which did not credit the heat pump system with the heat required to warm the leakage air from the attic up to the return air temperature from the house. At both air bases this factor was about 0.25 lower than the coefficient of performance for an outdoor temperature of 45°F and from 0.40 to 0.50 lower than the coefficient of performance at outdoor temperatures near the design value.

6. It was observed that 52 to 55 percent of the average energy used for all purposes in the sample dwellings at the two sites was used by the heat pump compressor and fans, the supplementary resistance heaters, and the bathroom heaters at Columbus AFB. The energy used for water heating ranged from 25 to 30 percent of the total, and the remainder of the energy, 17 to 20 percent, was used by the ranges, clothes dryers, and the miscellaneous devices. The ratio of the largest to the smallest usage of energy in the individual dwellings was typically about 2 to 1 for the heat pump and water heater, whereas this ratio was typically larger for the supplementary resistance heater, and was sometimes larger for the clothes dryer and cooking range.

7. The portion of the electric energy usage by the cooking range, water heater, and miscellaneous devices in each dwelling, that could reasonably be expected to contribute toward house heating, averaged about 2600 Btu/hr for the day and ranged from about 1400 Btu/hr during the eight-hour period after midnight to about 3700 Btu/hr during the eight-hour period before midnight.

8. The average power usage in the five sample dwellings at each base for all purposes varied with the time of day and with outdoor temperature. This average ranged from about 1 KW during the hours after midnight when the outdoor temperature was 65°F to about 7 KW during the daytime hours when the outdoor temperature was approximately 30°F, which was the lowest daytime temperature observed during the tests.

9. Energy-usage factors expressed in KW-hr/degree-day(1000 ft^2) were used to correlate energy usage, degree-days based on a 65°F reference temperature and inside floor area for the ten sample dwellings. These factors ranged from 2.32 to 2.97 for four of the sample houses at Seymour Johnson AFB and from 1.65 to 1.93 for four of the sample houses at Columbus AFB, whereas the factor was below this range in the fifth dwelling at each site. The values of the energy-usage factors were relatively stable for the range of outdoor temperature experienced during the tests, except that the factor became appreciably higher for very mild weather in several of the dwellings at Seymour Johnson AFB. Some of the design factors at Seymour Johnson AFB which probably contributed to higher energy-usage factors at this site are: (a) the balance point temperature was higher, (b) loss of heating capacity in the refrigerant lines connecting indoor and outdoor units, (c) little or no recovery of heat from the attic-mounted system when the blower was stopped, and (d) use of bathroom heaters at Columbus AFB.

10. The observed heat requirements of the sample dwellings during normal operation of the heat pump system agreed with those determined by calibration with resistance heaters at the same outdoor temperatures in most cases. Since the design wind velocity of 15 mph did not occur in combination with design outdoor temperature during the test period at either site, no direct comparison of observed heat loss and calculated heat loss at this condition was possible. However, when the observed values were corrected for increased heat transmission through the windows and increased attic air leakage corresponding to a 15-mph wind, comparisons between these corrected values and the calculated values were possible. It was found that the calculated heat loss at design outdoor conditions and with an infiltration rate of one air change per hour at outdoor temperature exceeded the calibration heat loss, after correction, by amounts ranging from 7 to 21 percent in the five sample dwellings at Seymour Johnson AFB. This comparison indicates that the combination of normal infiltration and air leakage from the attic may not have created a heating load as large as one air change per hour at outdoor temperature at this site. At Columbus AFB the calculated heat loss at design outdoor conditions and with an infiltration rate of one air change per hour at outdoor temperature bracketed the calibration heat loss, after correction. The calculated values ranged from 6 percent below to 10 percent above the corrected values based on the calibration tests, indicating that, on the average, the heating load of the overall leakage of air by normal infiltration and attic leakage may have approximated that caused by one air change per hour of air at outdoor temperature. The significance of the 15-mph wind in augmenting the heating load of these dwellings was made evident by these comparisons.

11. The sample dwellings selected for study at each site were fairly representative of the entire project with respect to average energy use even though the proportion of dwellings of the several types differed in the two groups. The average energy use in the five sample dwellings at Seymour Johnson AFB was 95.3% of the average for the 1500 dwellings comprising the project, whereas the average energy use of the five sample dwellings at Columbus AFB was 99.1% of the average for the 480 dwellings in the project, during the 31-day periods available for comparison.

Acknowledgment:

The cooperation and assistance received from the occupants of the ten sample houses, from civilian and military personnel at the two bases who participated in the tests, and from staff members of the National Bureau of Standards who assisted in the conduct of the study and analysis of the data is gratefully acknowledged.

Fig. 1. Front view, type C (left) and D dwellings, Seymour Johnson AFB

Fig. 2. Front view, type E house, Seymour Johnson AFB

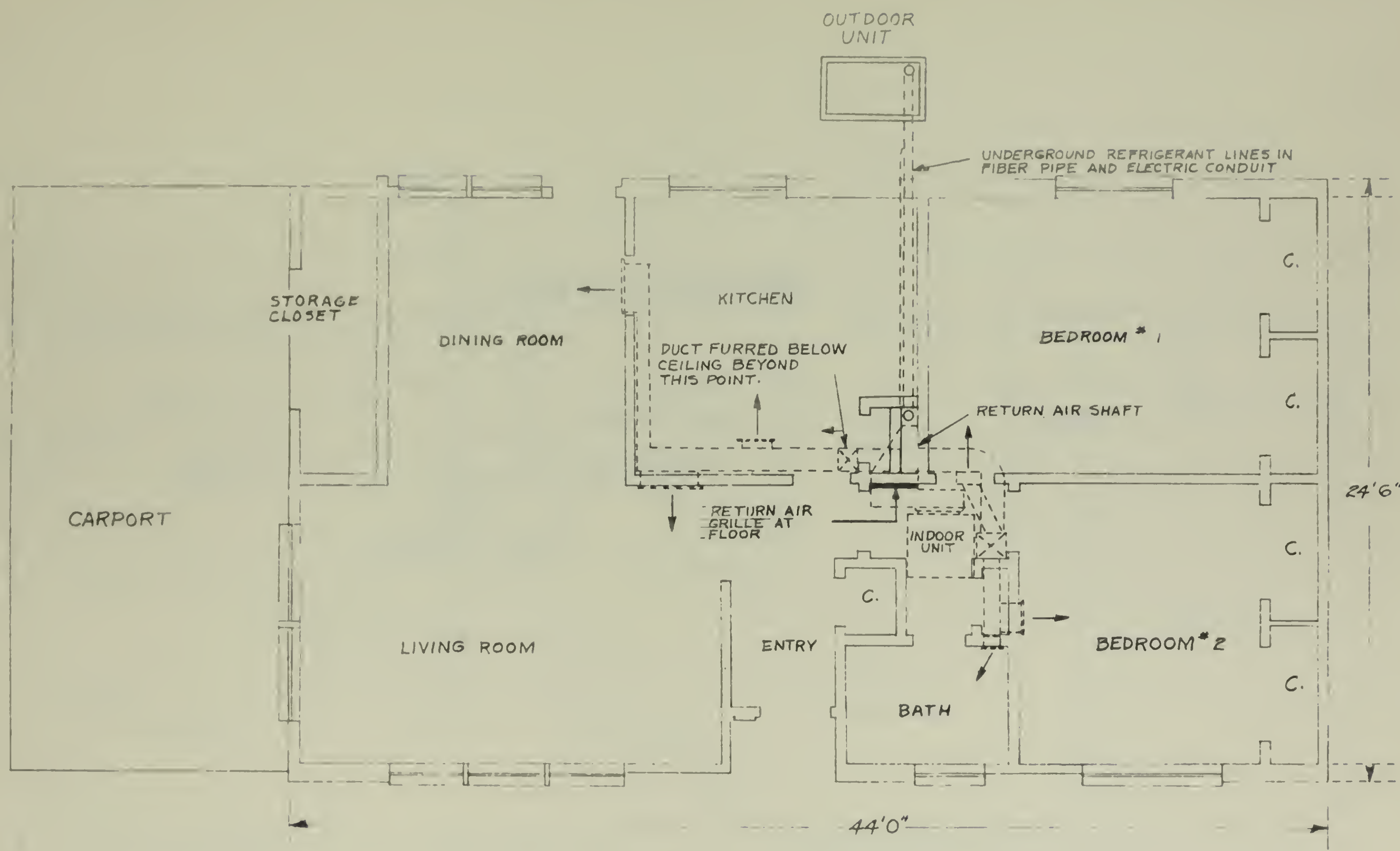

Fig. 3. Plan View of Type A House, Seymour Johnson Air Force Base

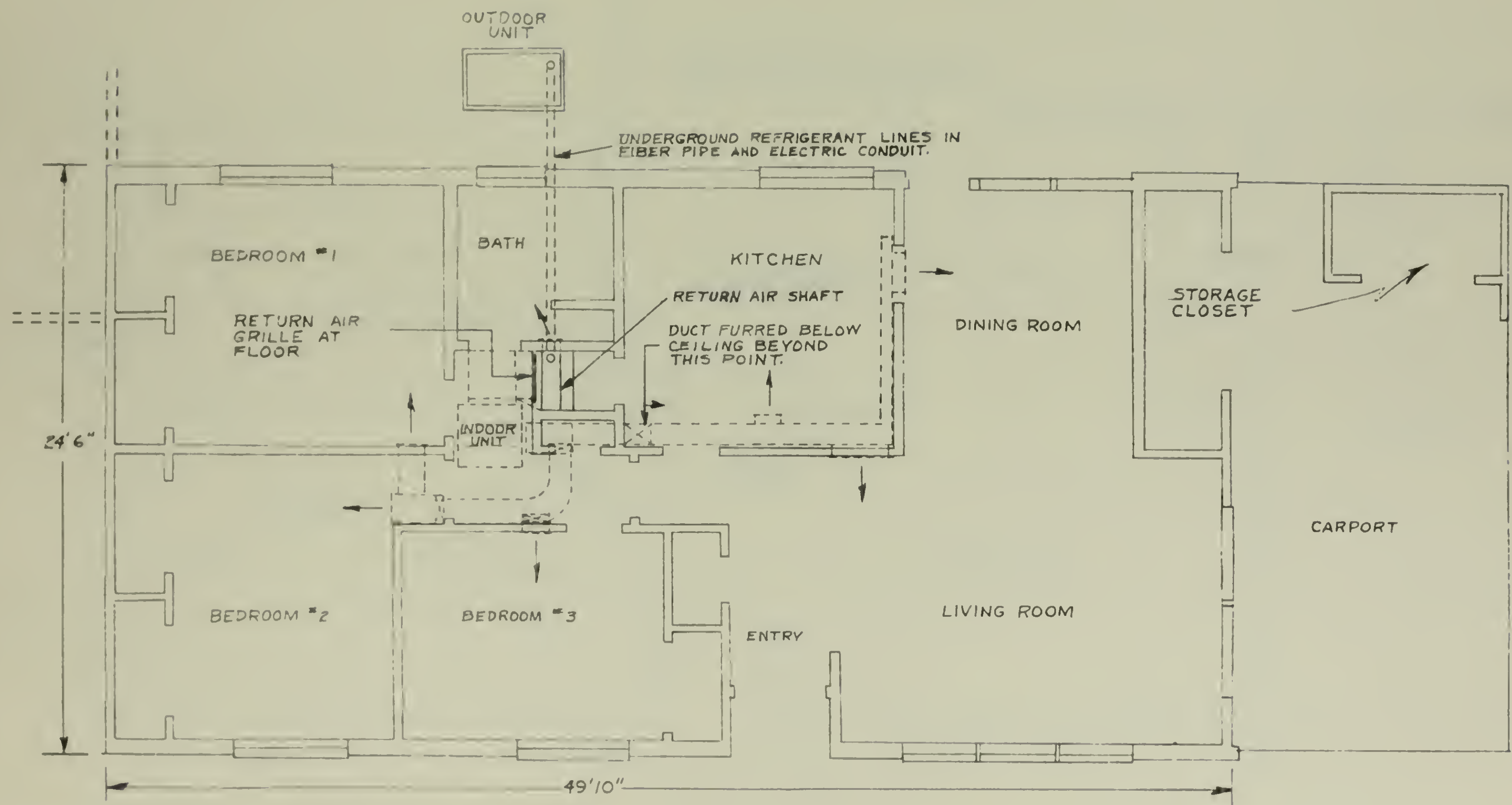

Fig. 4. Plan View of Type B House, Seymour Johnson Air Force Base

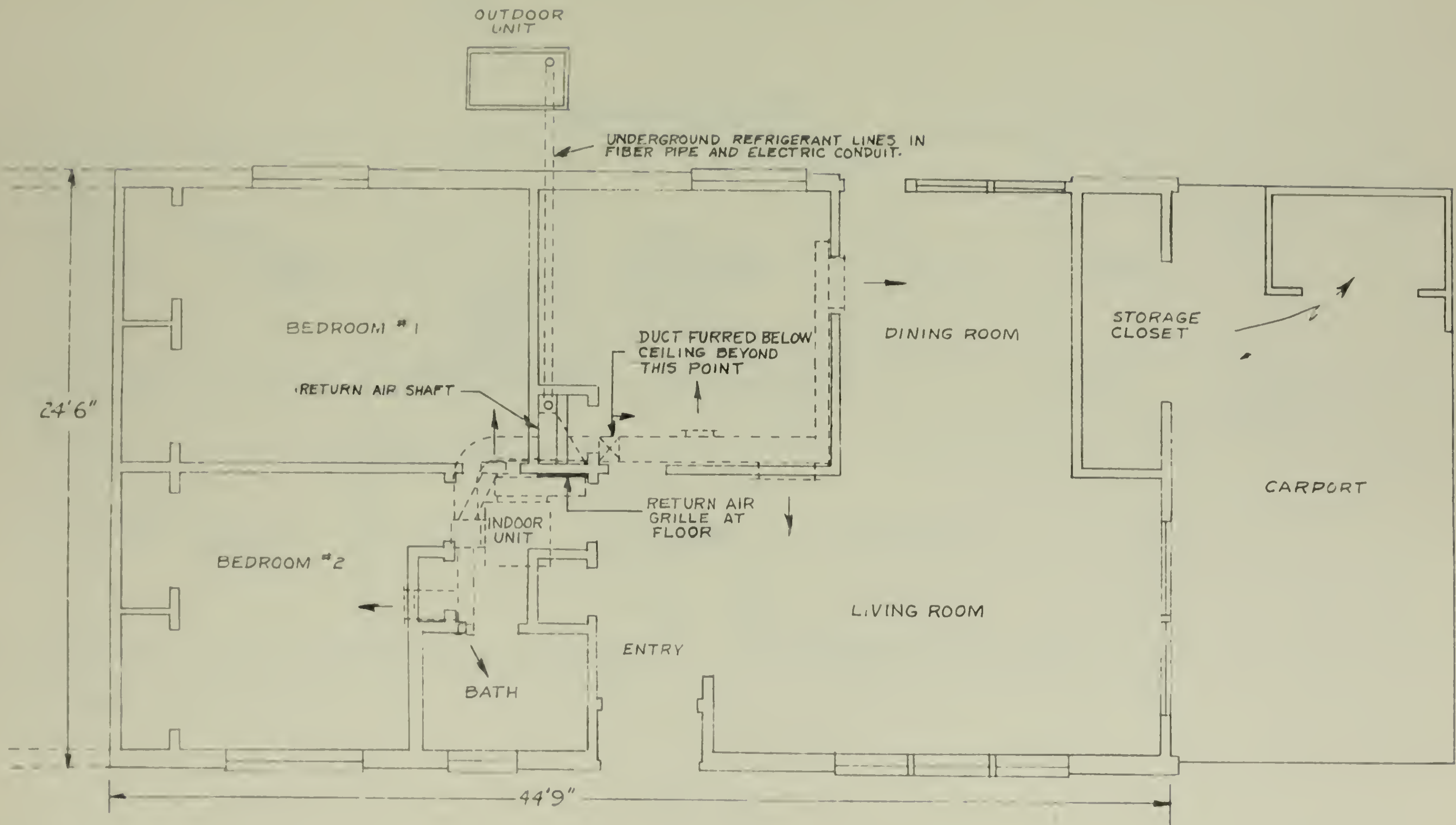

Fig. 5. Plan View of Type C House, Seymour Johnson Air Force Base

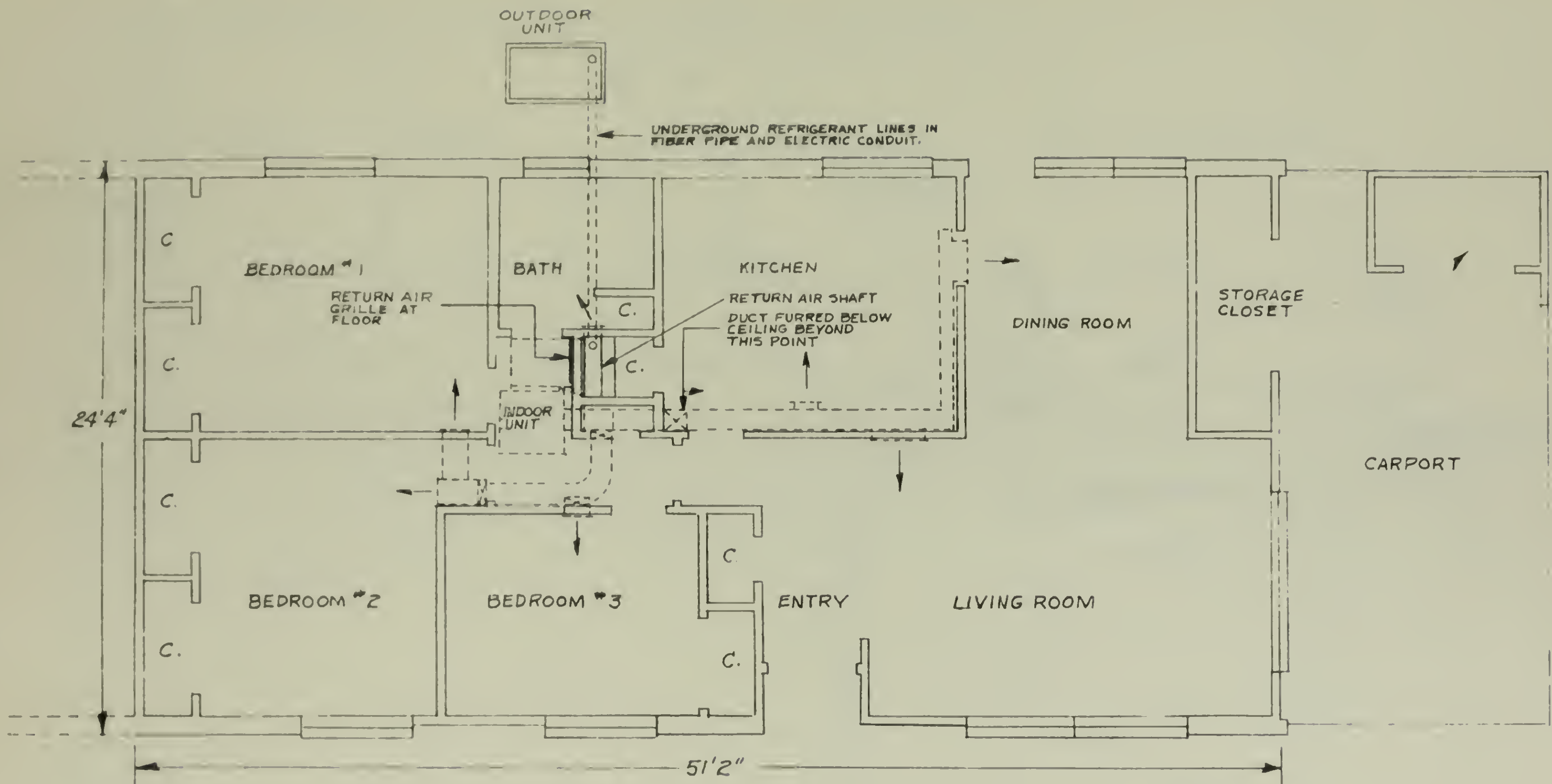

Fig. 6. Plan View of Type D House, Seymour Johnson Air Force Base

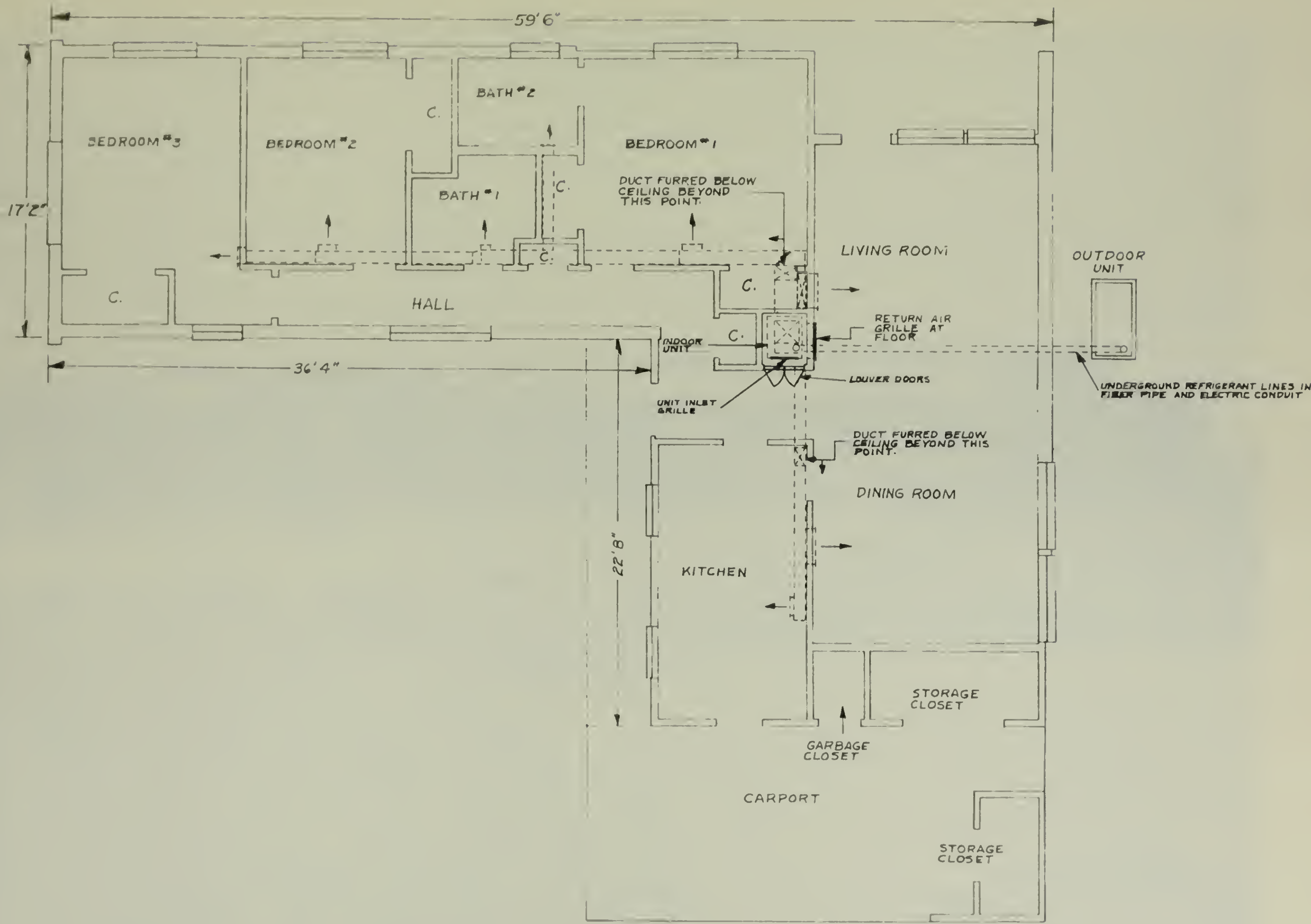

Fig. 7. Plan View of Type E House, Seymour Johnson Air Force Base

Fig. 8. Front view of two type A3D1 dwellings, Columbus AFB

Fig. 9. Front view of type 03S3 house, Columbus AFB

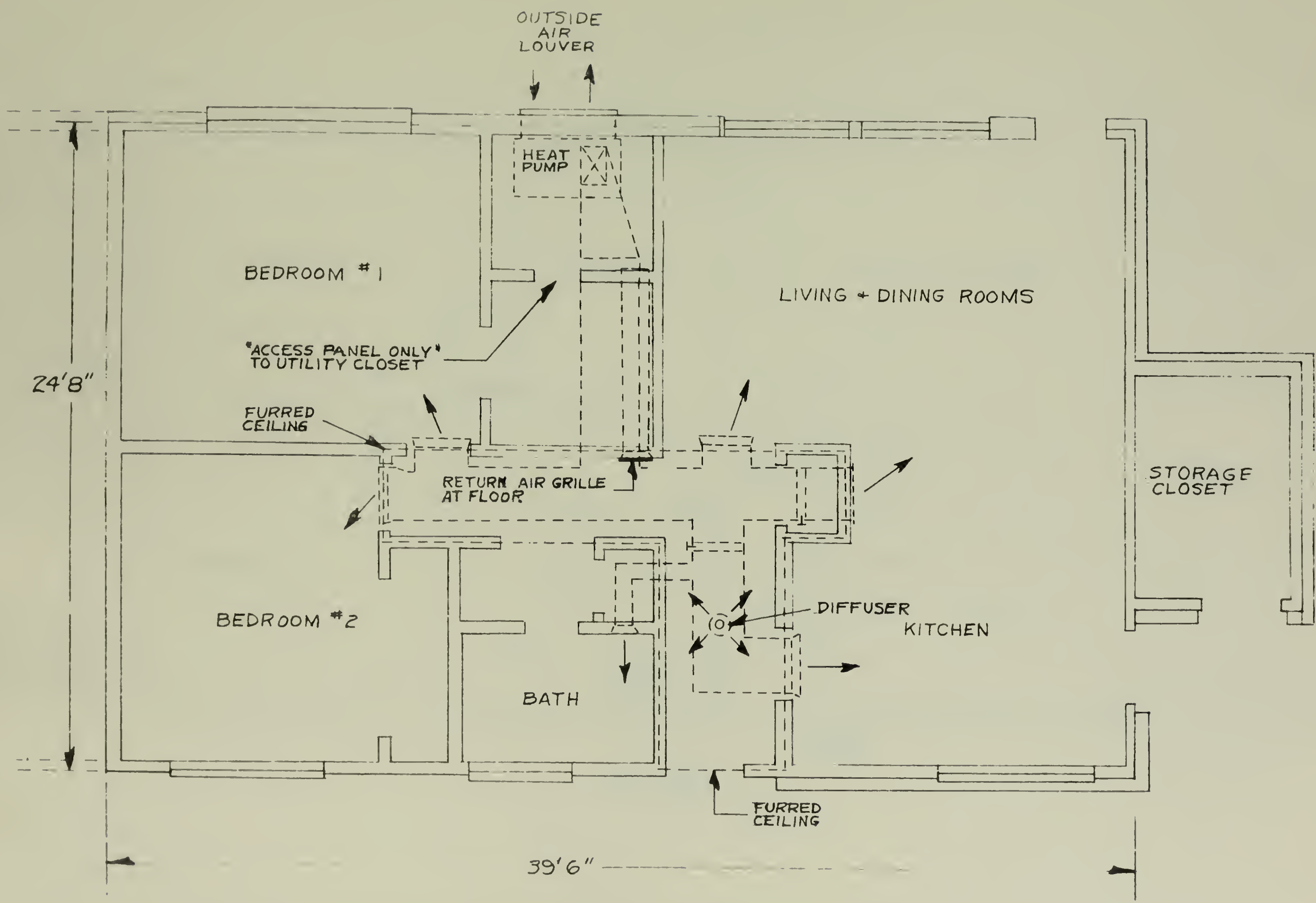

Fig. 10. Plan View of Type A2D1 House, Columbus Air Force Base

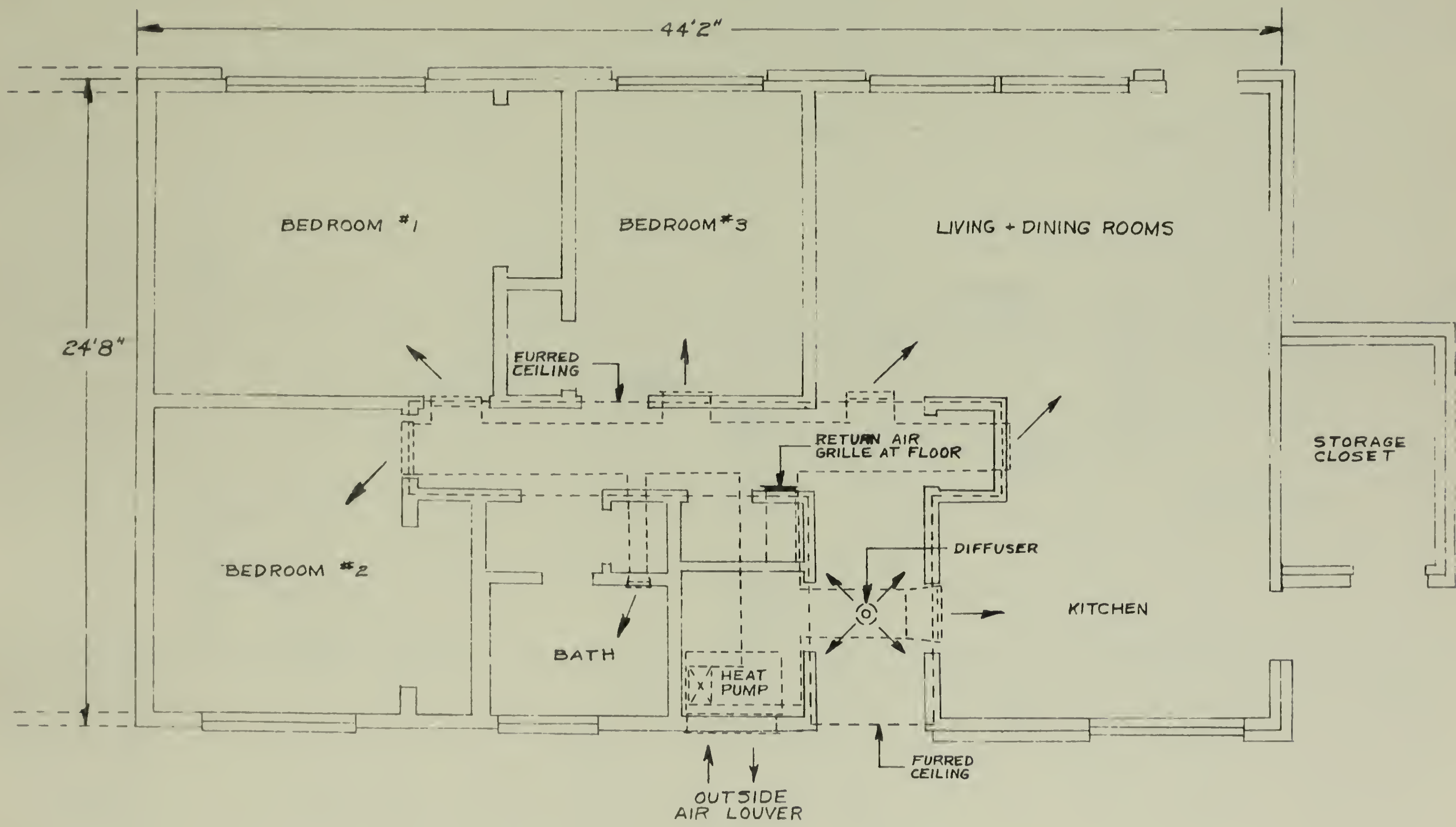

Fig. 11. Plan View of Type A3D1 House, Columbus Air Force Base

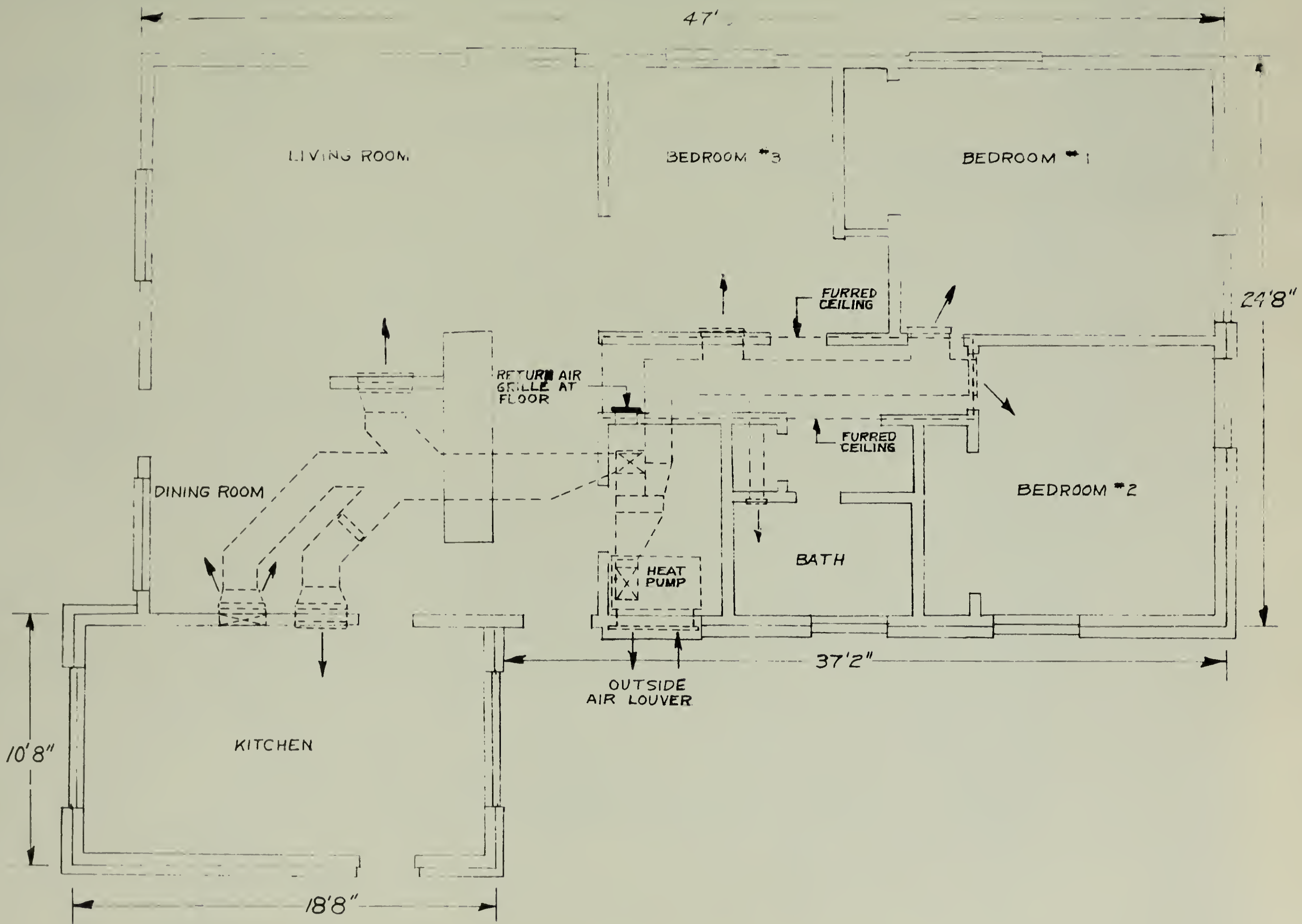

Fig. 12. Plan View of Type 03S3 House, Columbus Air Force Base

Fig. 13. Attic installation of indoor unit viewed through trap door, Seymour Johnson AFB

Fig. 14. Indoor unit in type E house viewed through closet door, Seymour Johnson AFB

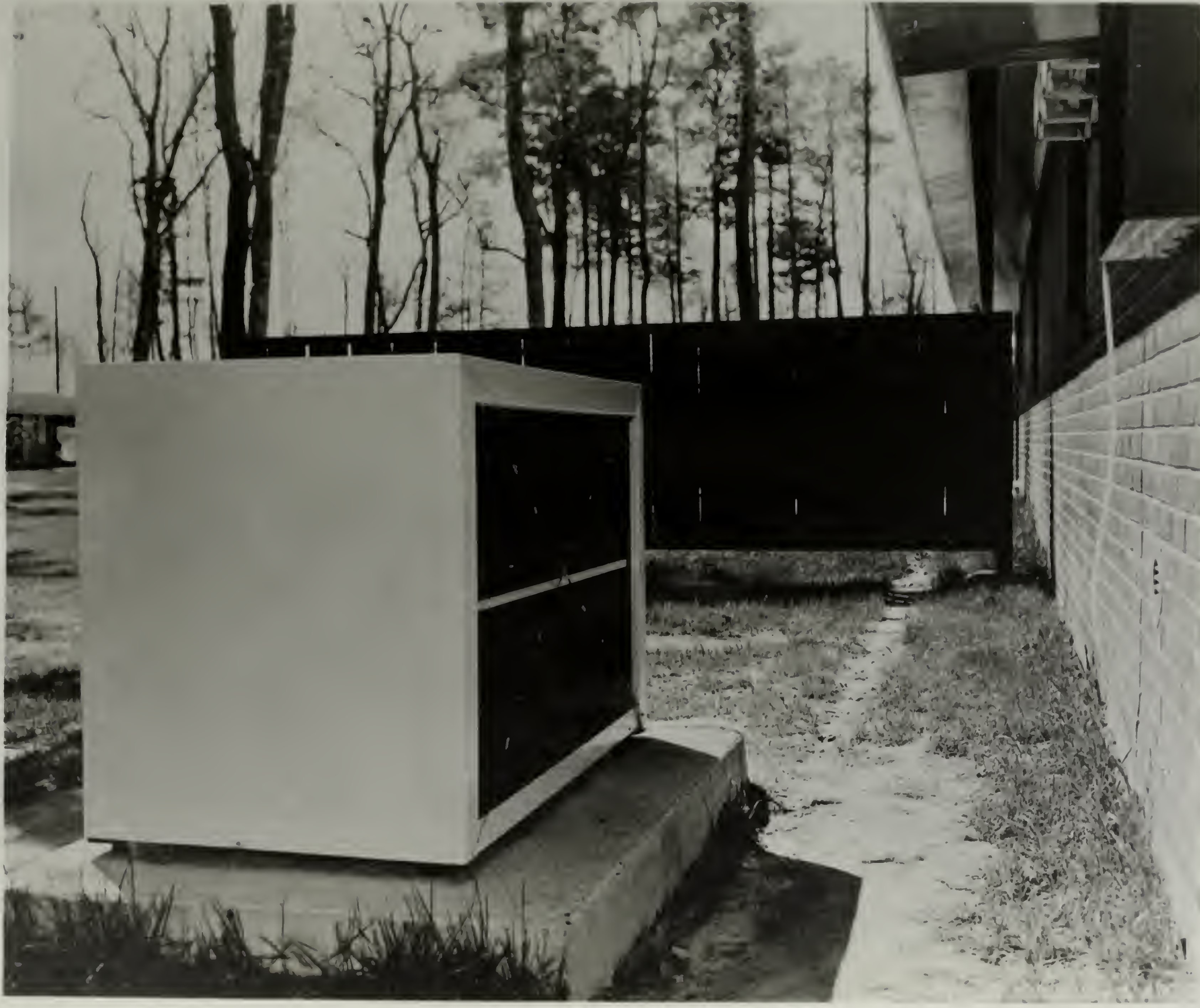

Fig. 15. Typical location of outdoor unit, Seymour Johnson AFB

Fig. 16. Typical installation of unitary heat pump in utility closet, Columbus AFB

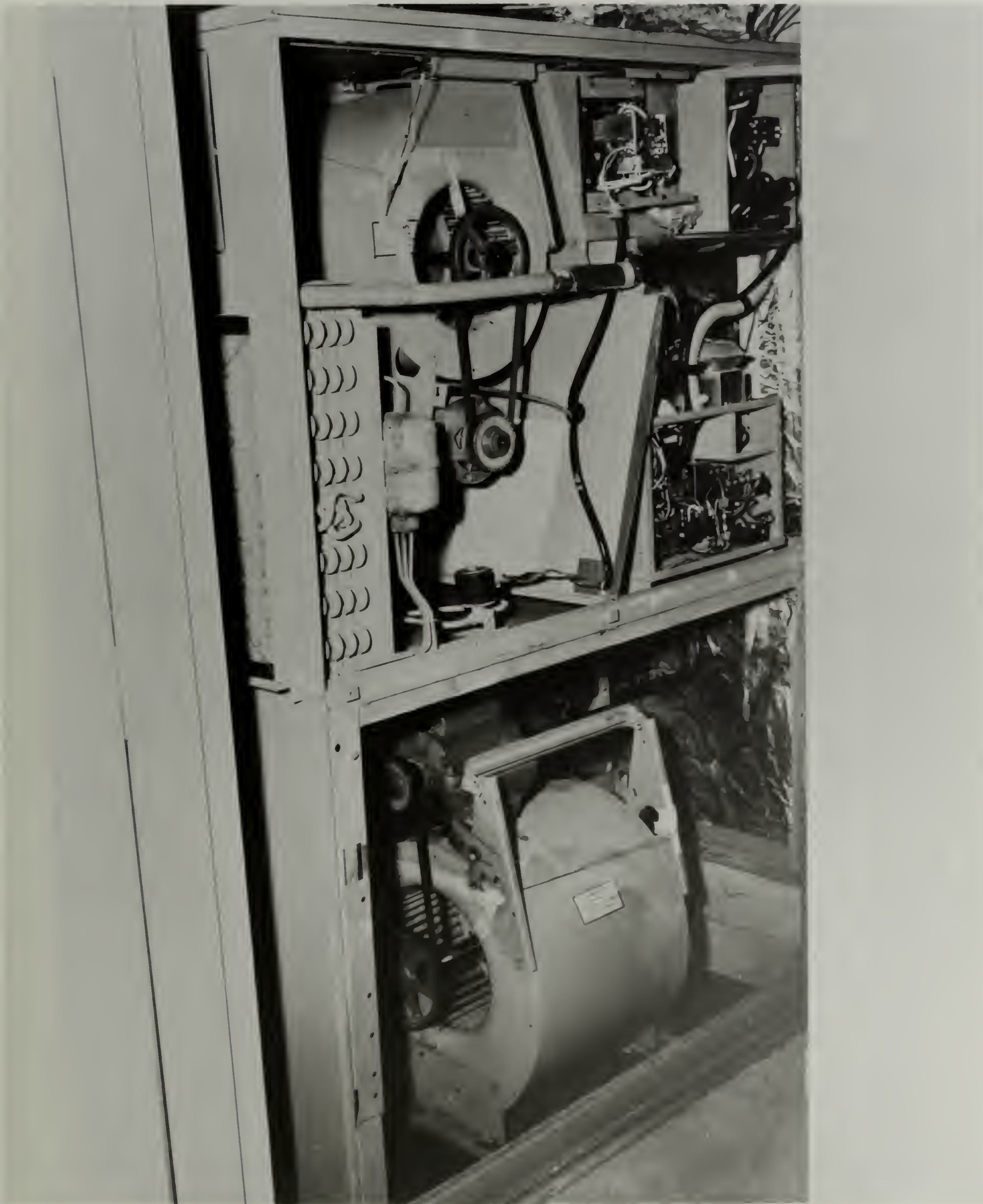

Fig. 17. View of typical unitary heat pump with front panel removed, Columbus AFB

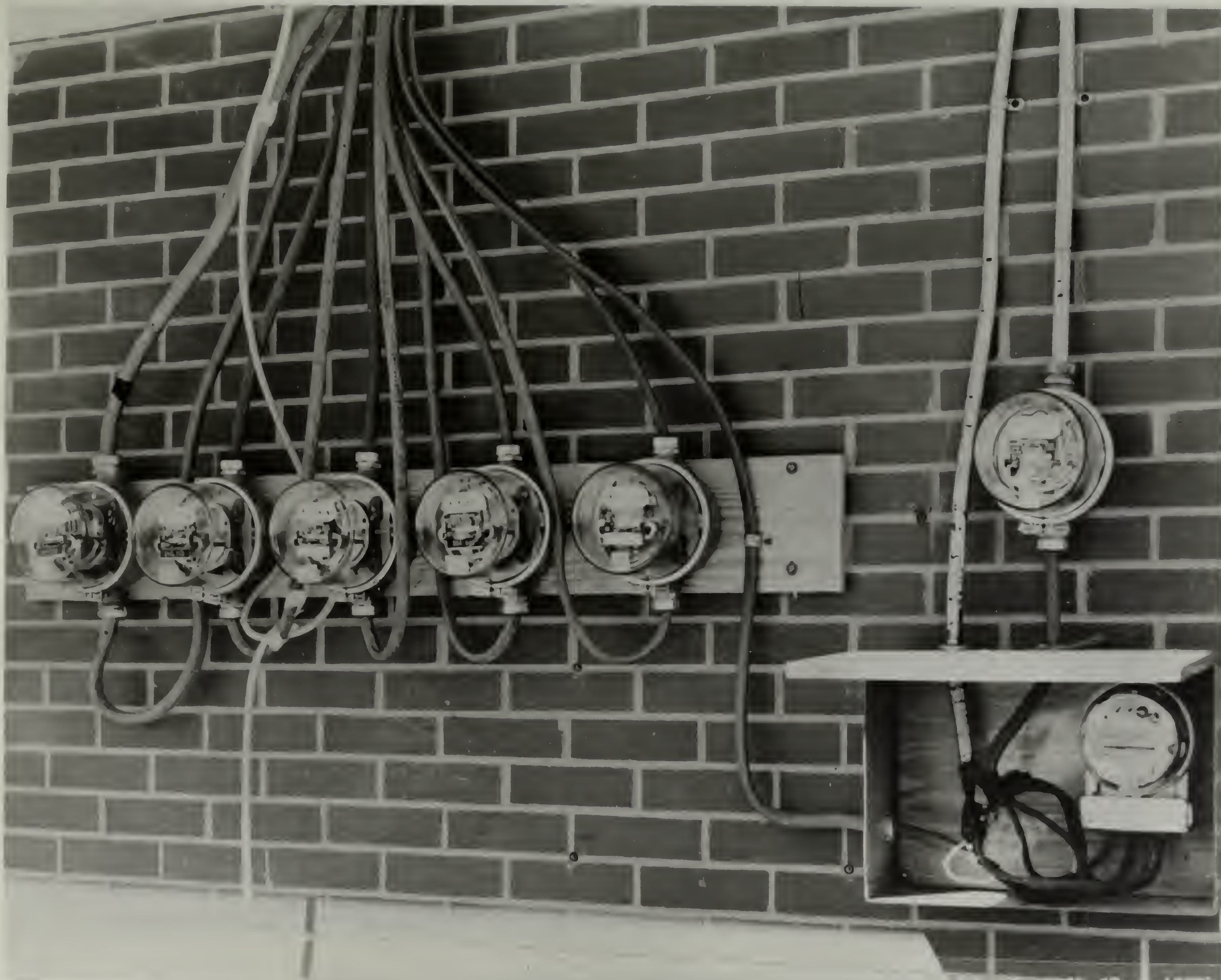

Fig. 18. Typical installation of watthour meters, Seymour Johnson AFB

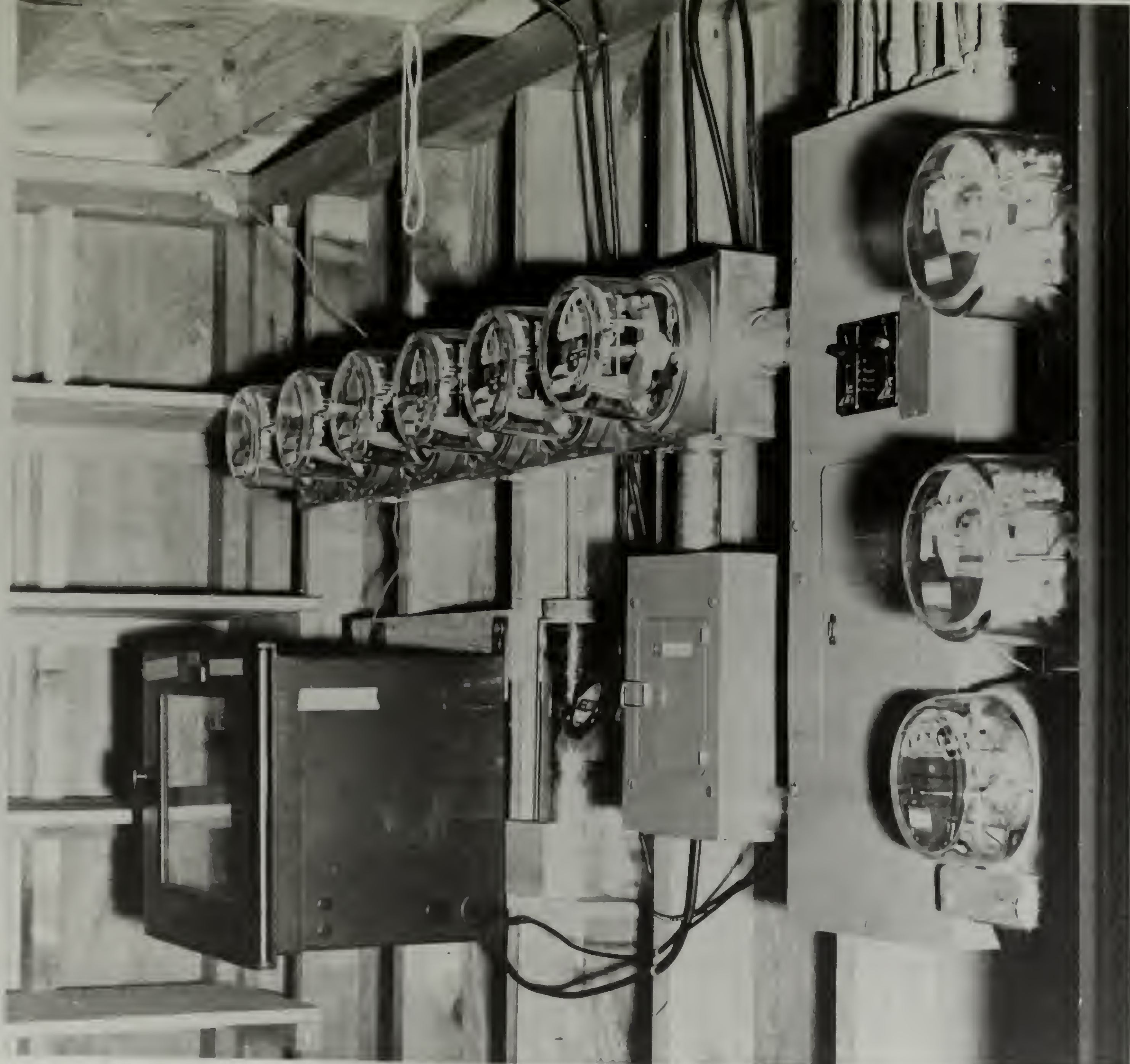

Fig. 19. Typical installation of watthour meters, Columbus AFB

Fig. 20. Typical installation of pyrheliometer and outdoor air thermocouple

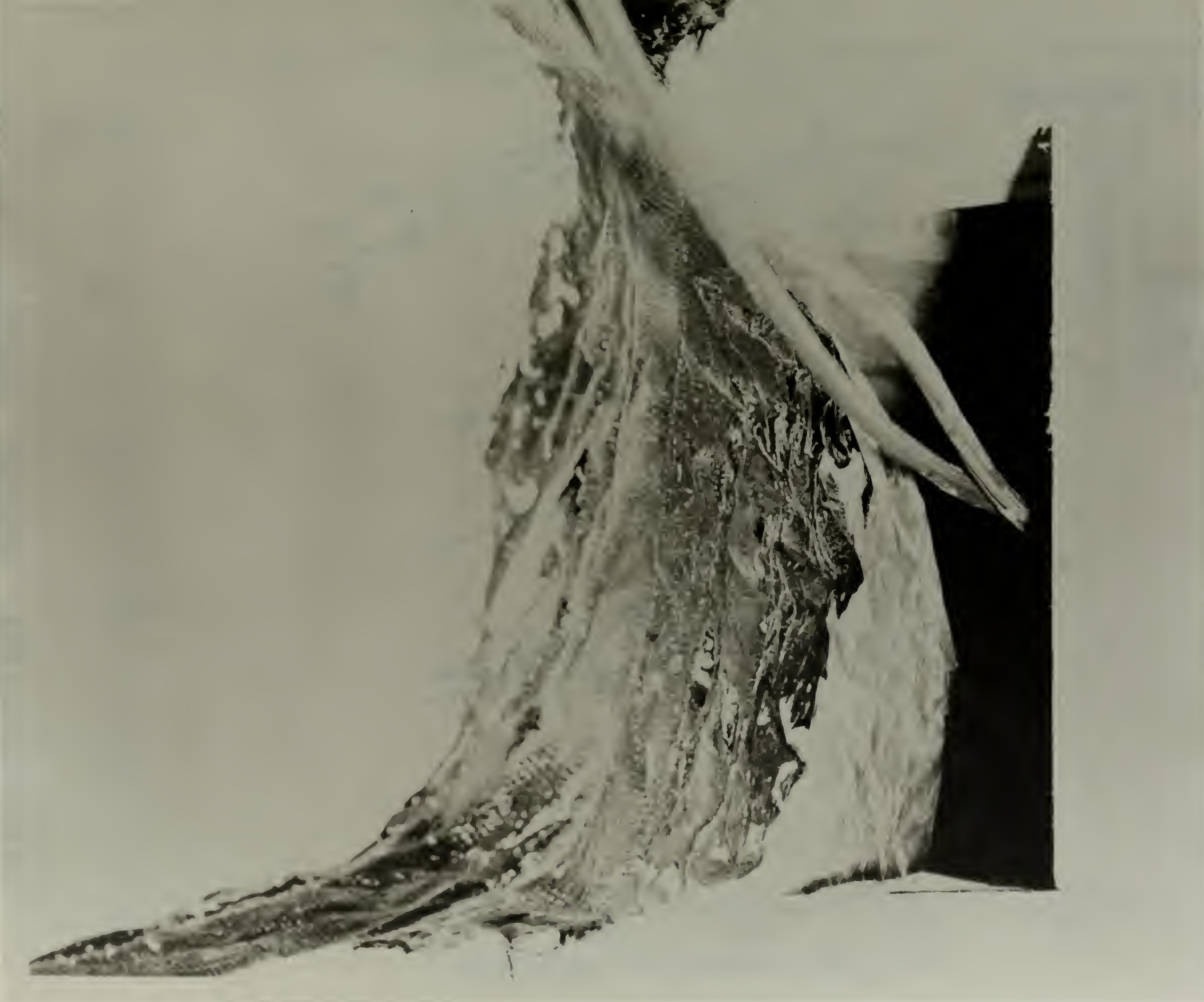

Fig. 21. View showing path for air leakage (dark area at right) from attic into utility closet, Columbus AFB

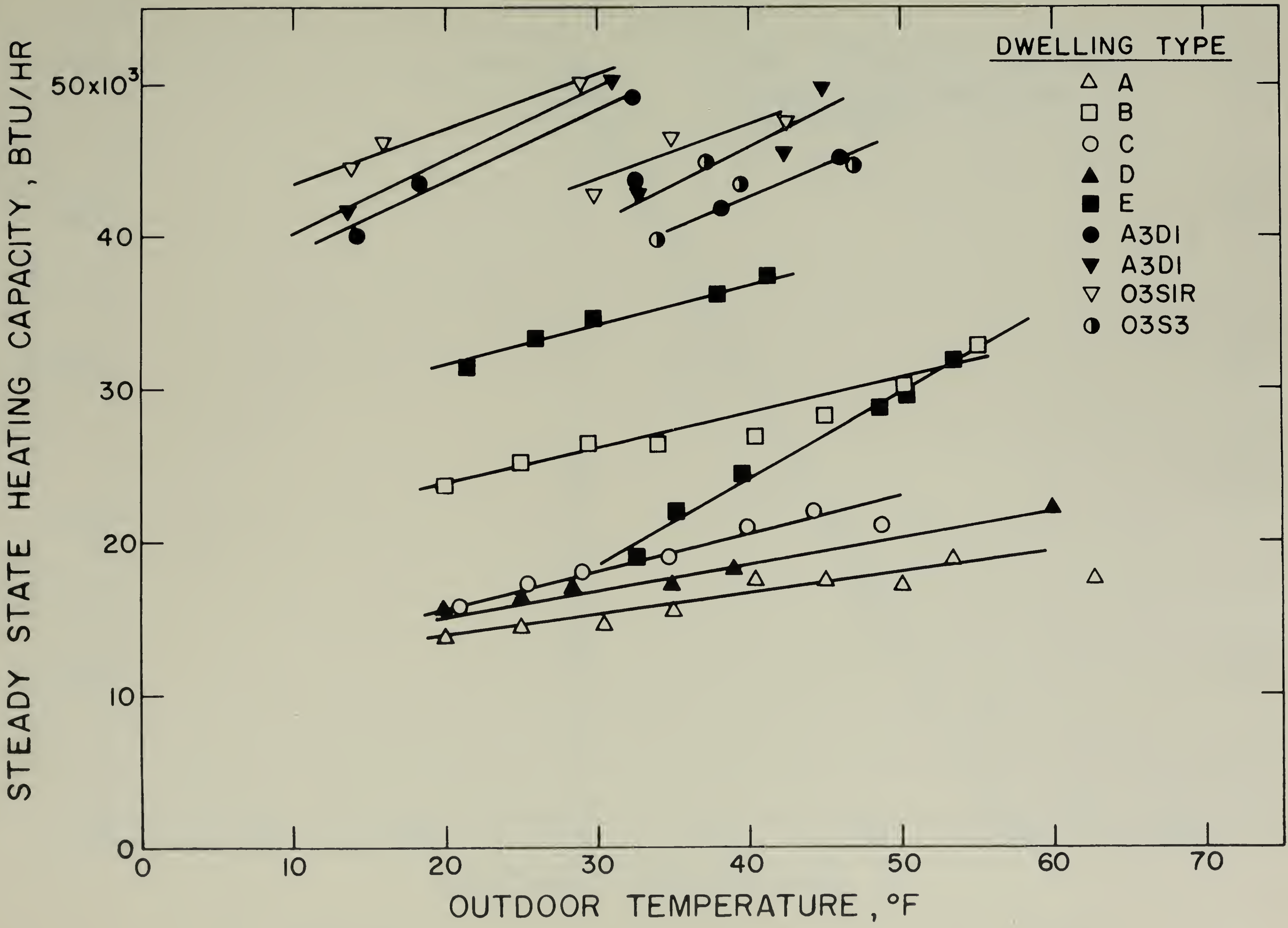

Fig. 22. Steady State Heating Capacity of the Compression System in Nine Sample Houses for a Range of Outdoor Temperature

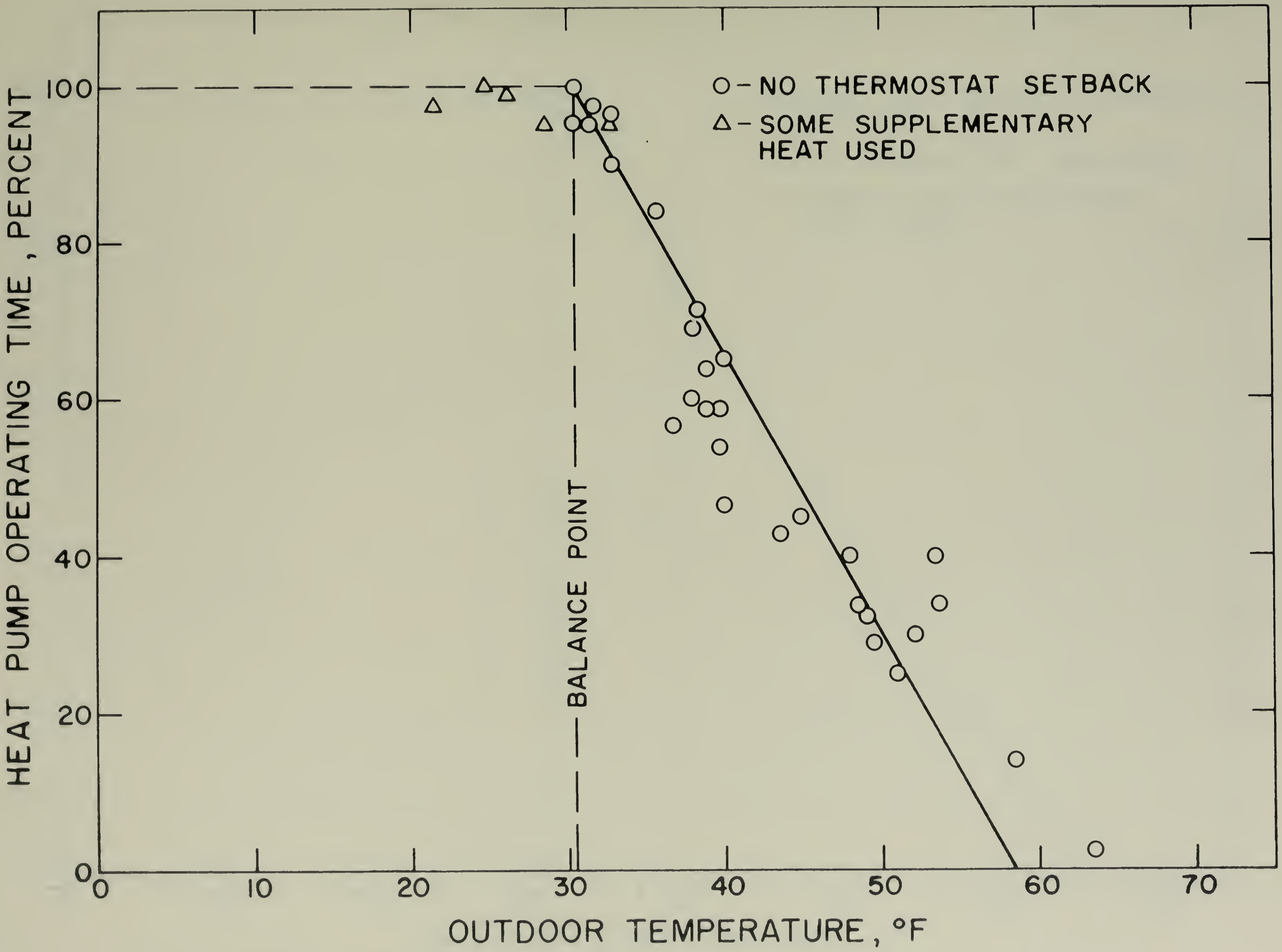

Fig. 23. Operating Time and Balance Point of the Heat Pump in the Type A Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

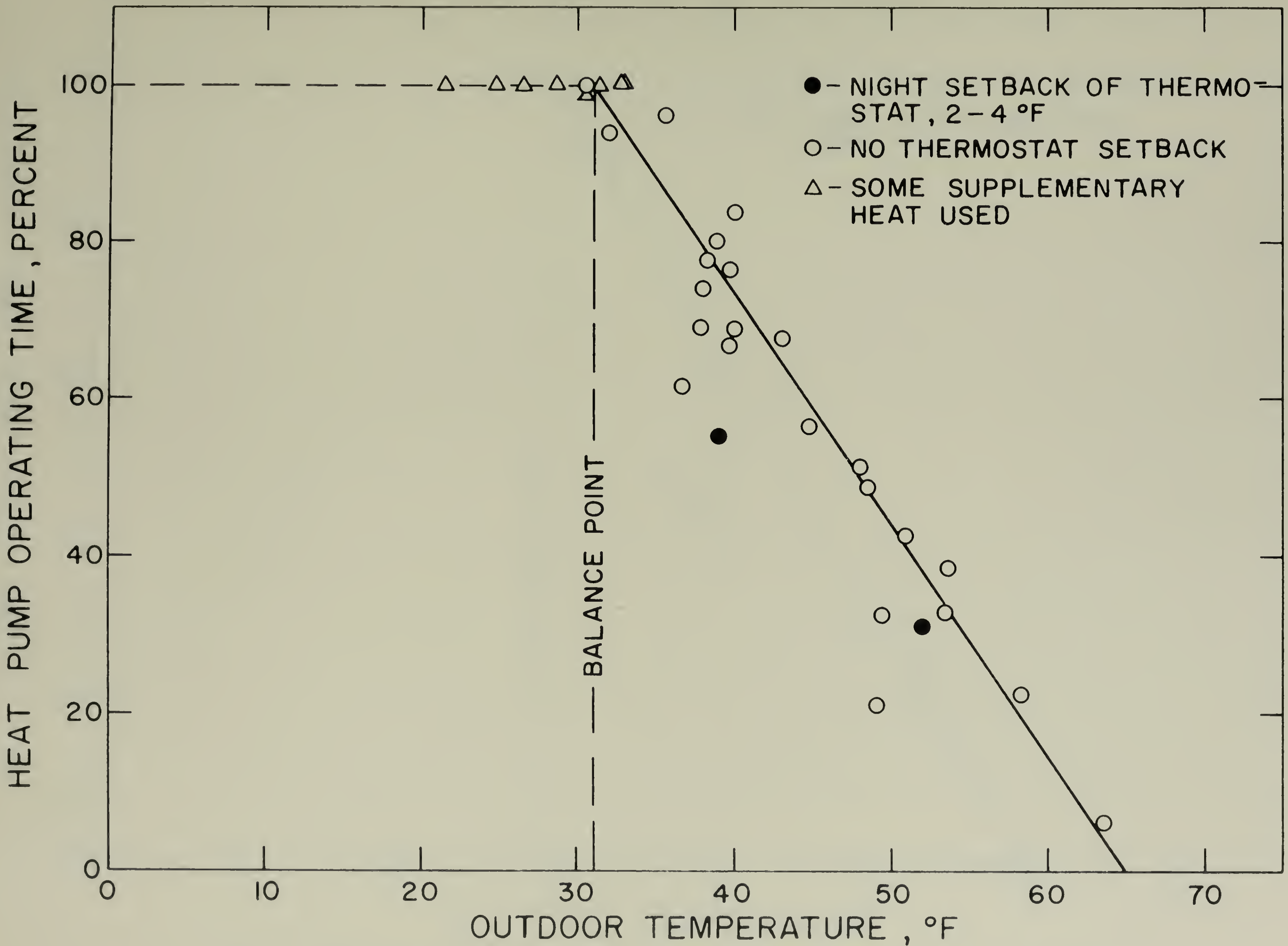

Fig. 24. Operating Time and Balance Point of the Heat Pump in the Type B Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

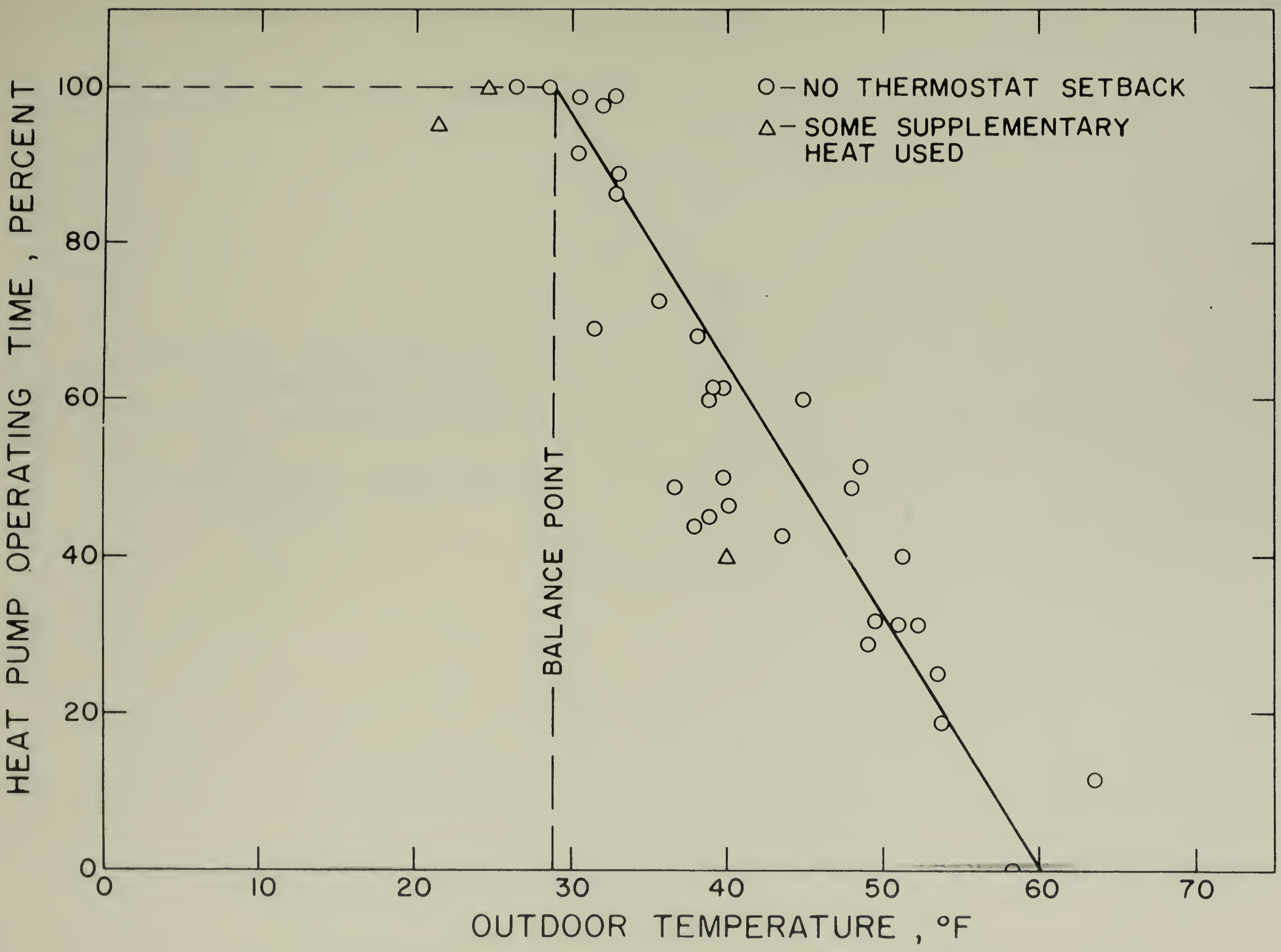

Fig. 25. Operating Time and Balance Point of the Heat Pump in the Type C Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

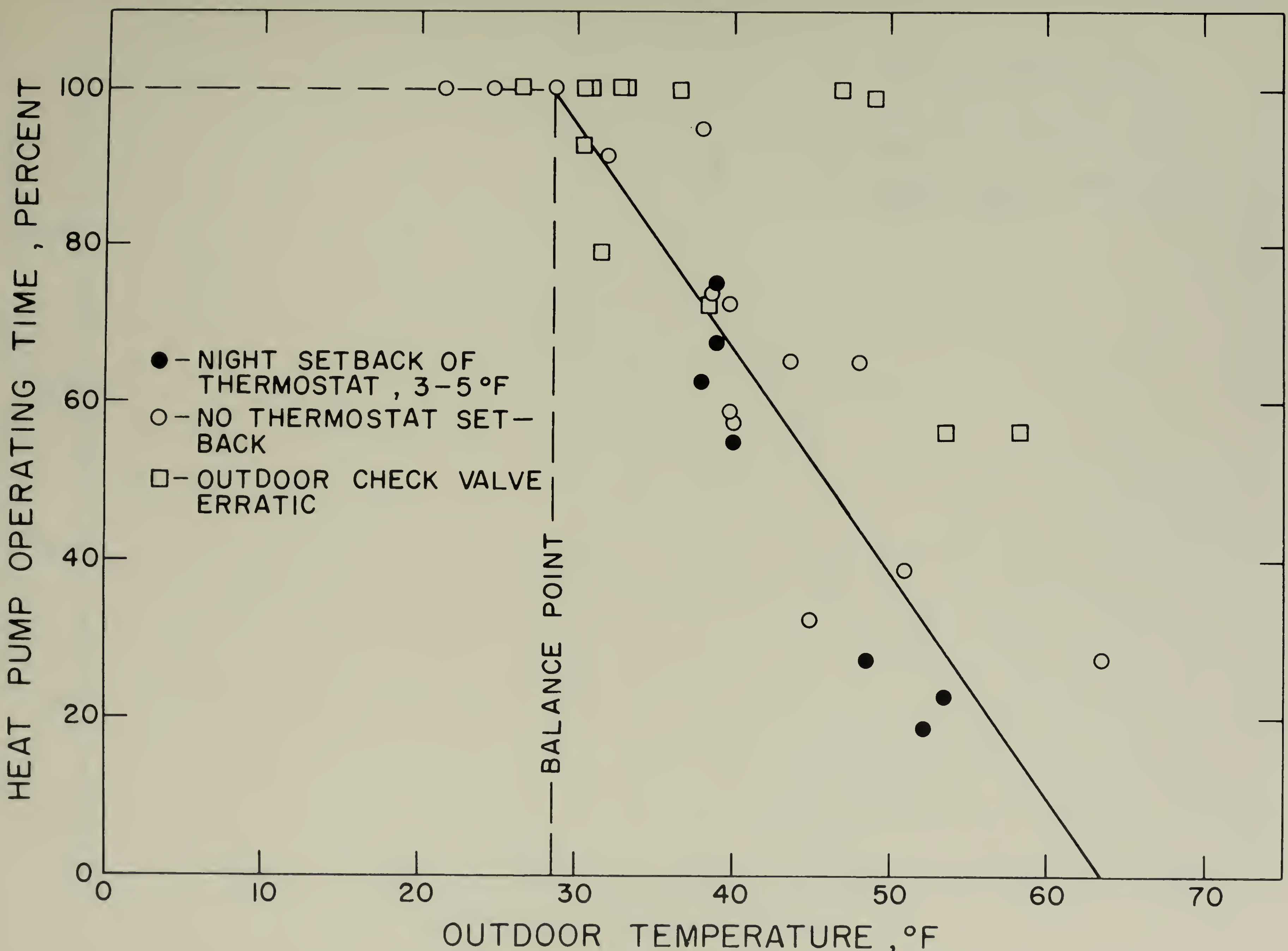

Fig. 26. Operating Time and Balance Point of the Heat Pump in the Type D Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

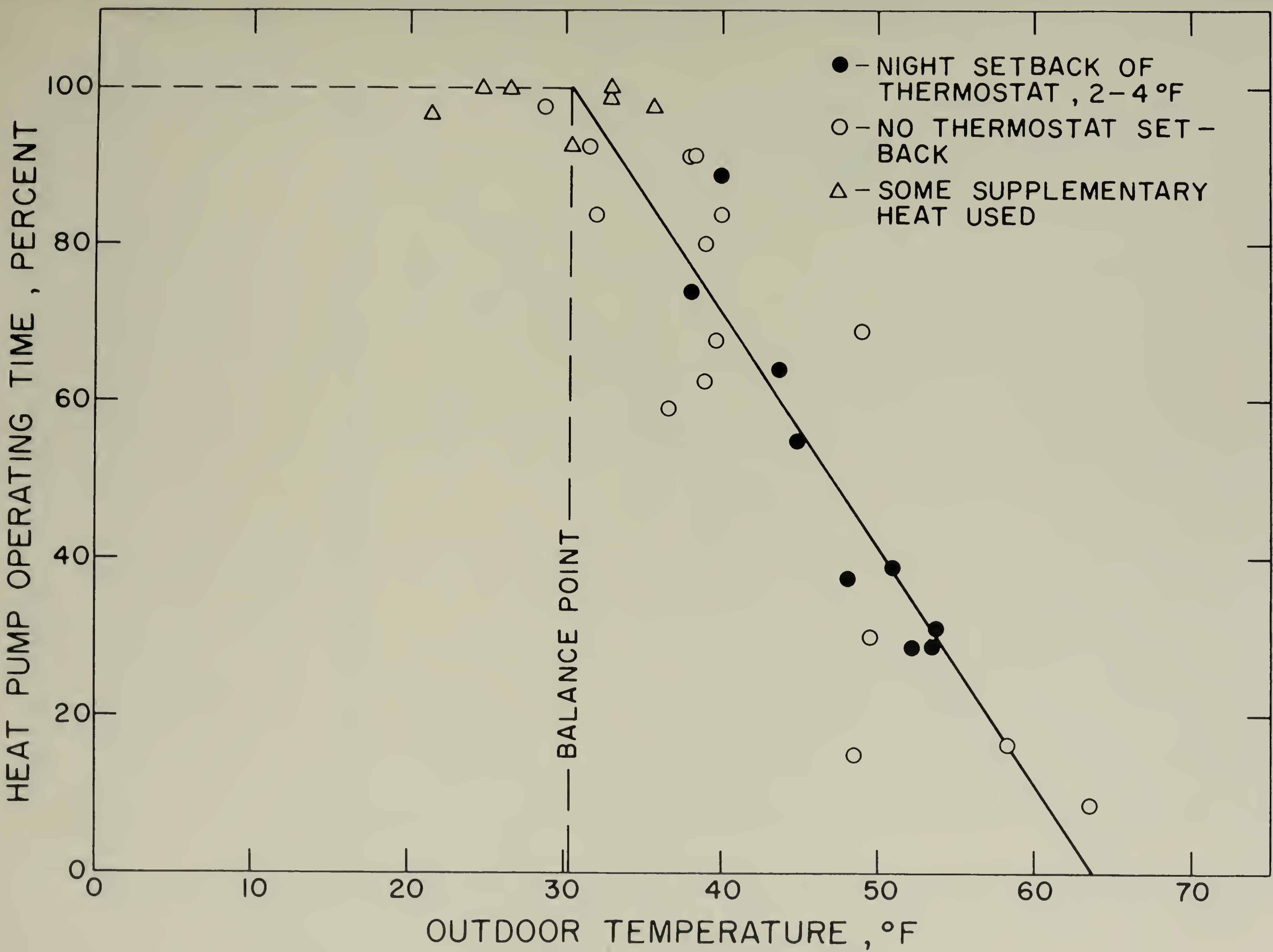

Fig. 27. Operating Time and Balance Point of the Heat Pump in the Type E House, Seymour Johnson AFB, for a Range of Outdoor Temperature

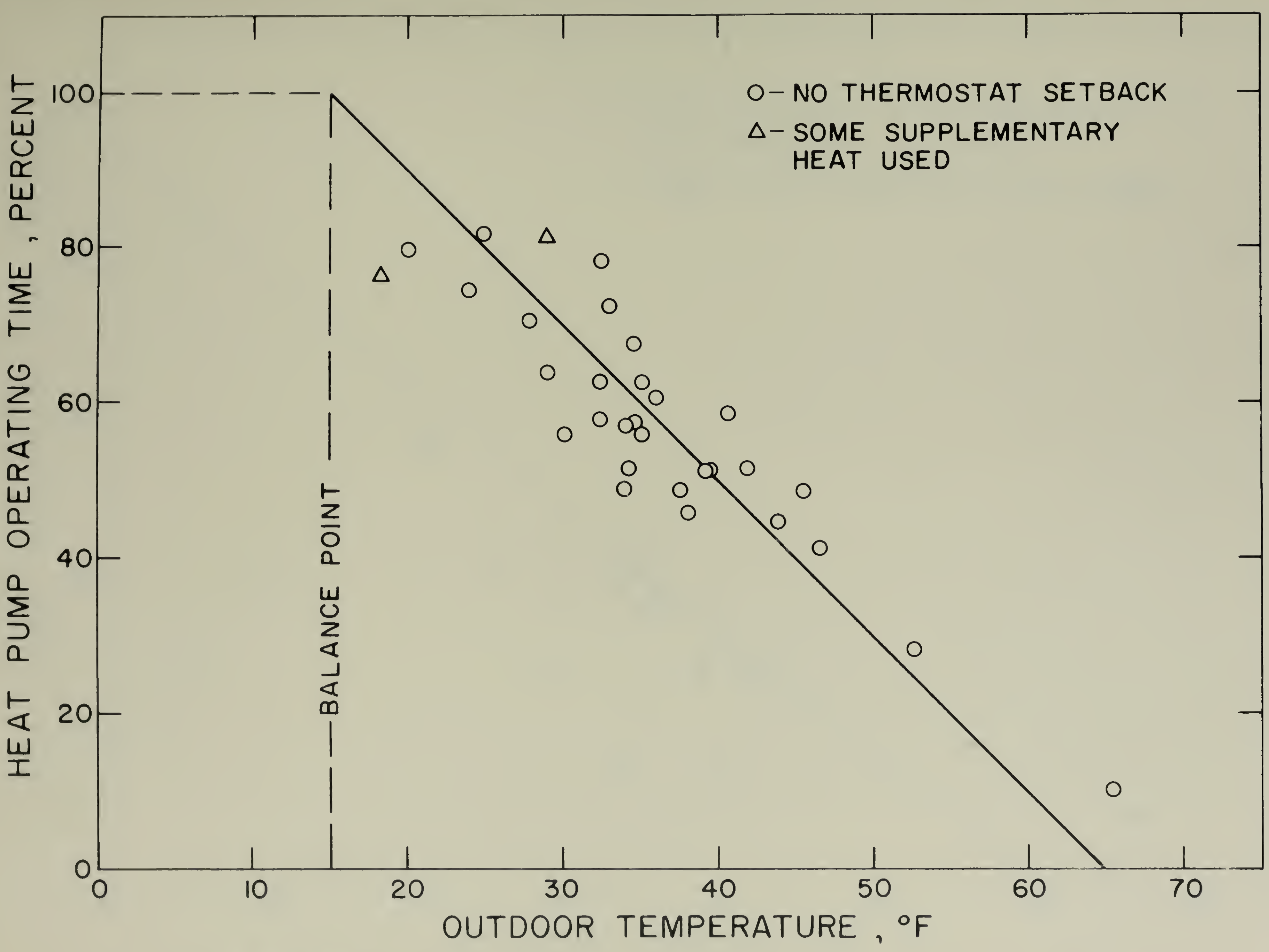

Fig. [illegible]. Operating Time and Balance Point of the Heat Pump in the Type 03S1R House, Columbus AFB, for a Range of Outdoor Temperature

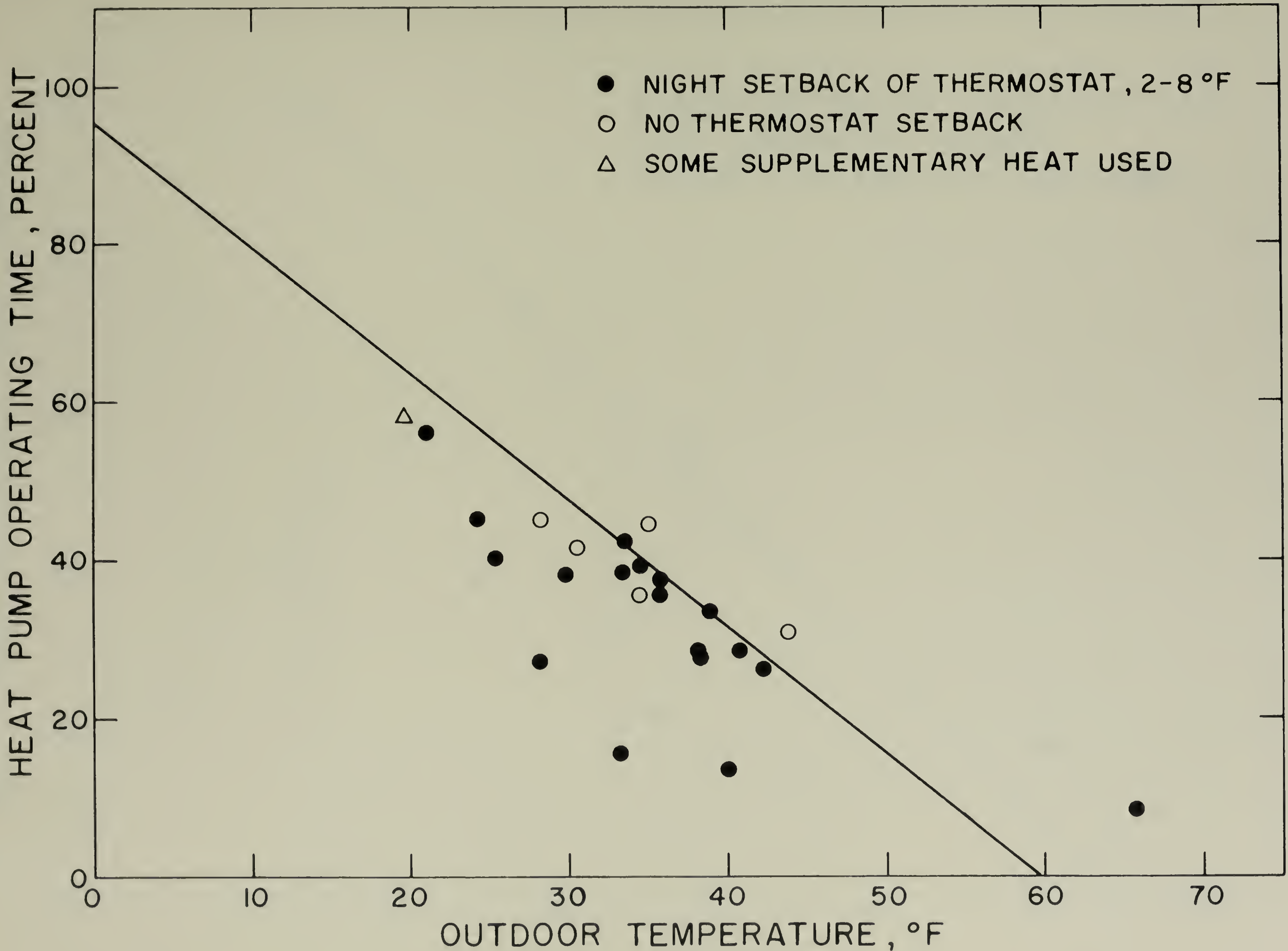

Fig. 29. Operating Time and Balance Point of the Heat Pump in the Type A3D1 Dwelling, Columbus AFB, for a Range of Outdoor Temperature

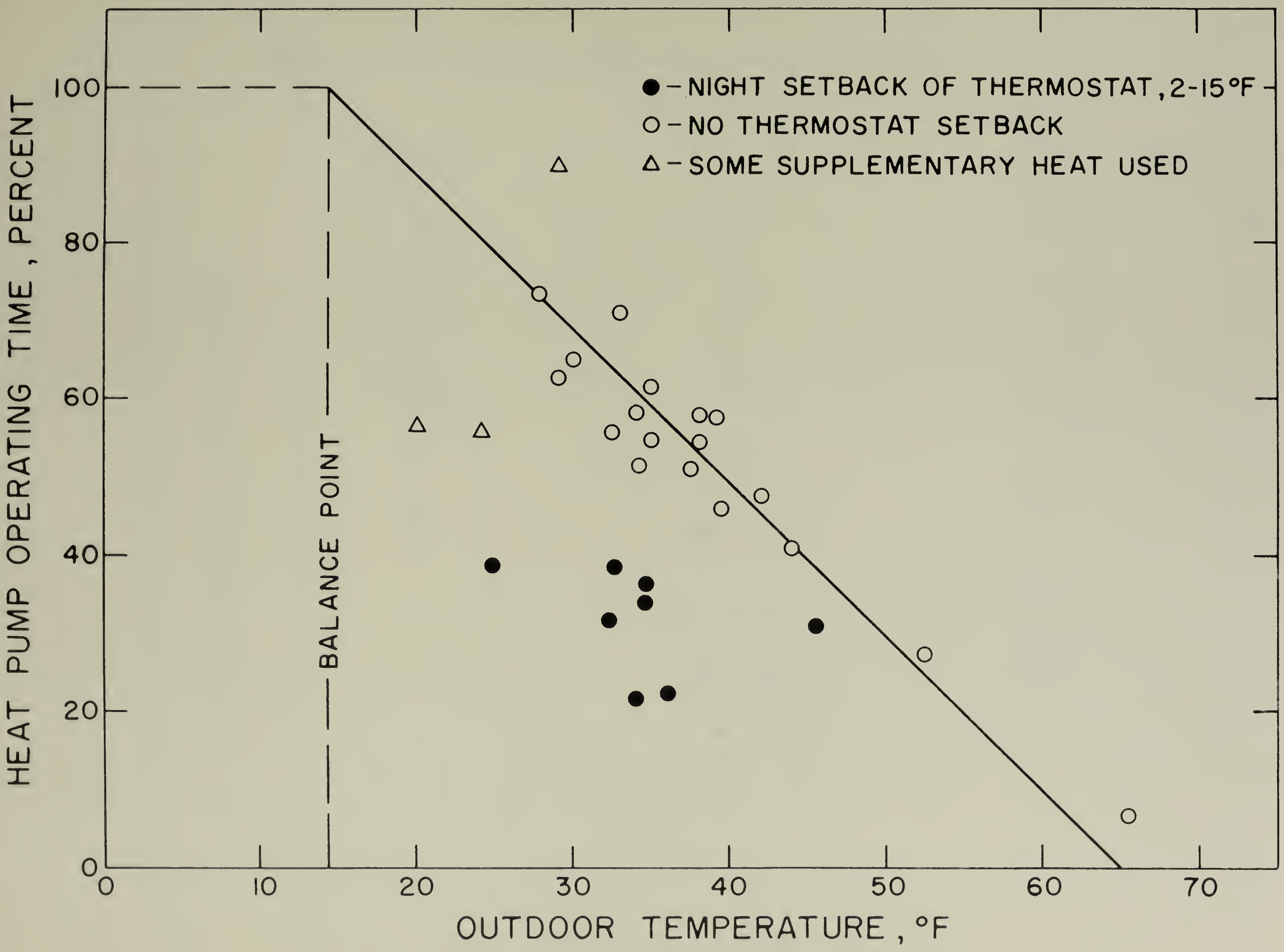

Fig. 30. Operating Time and Balance Point of the Heat Pump in the Type [illegible] House, Columbus AFB, for a Range of Outdoor Temperature

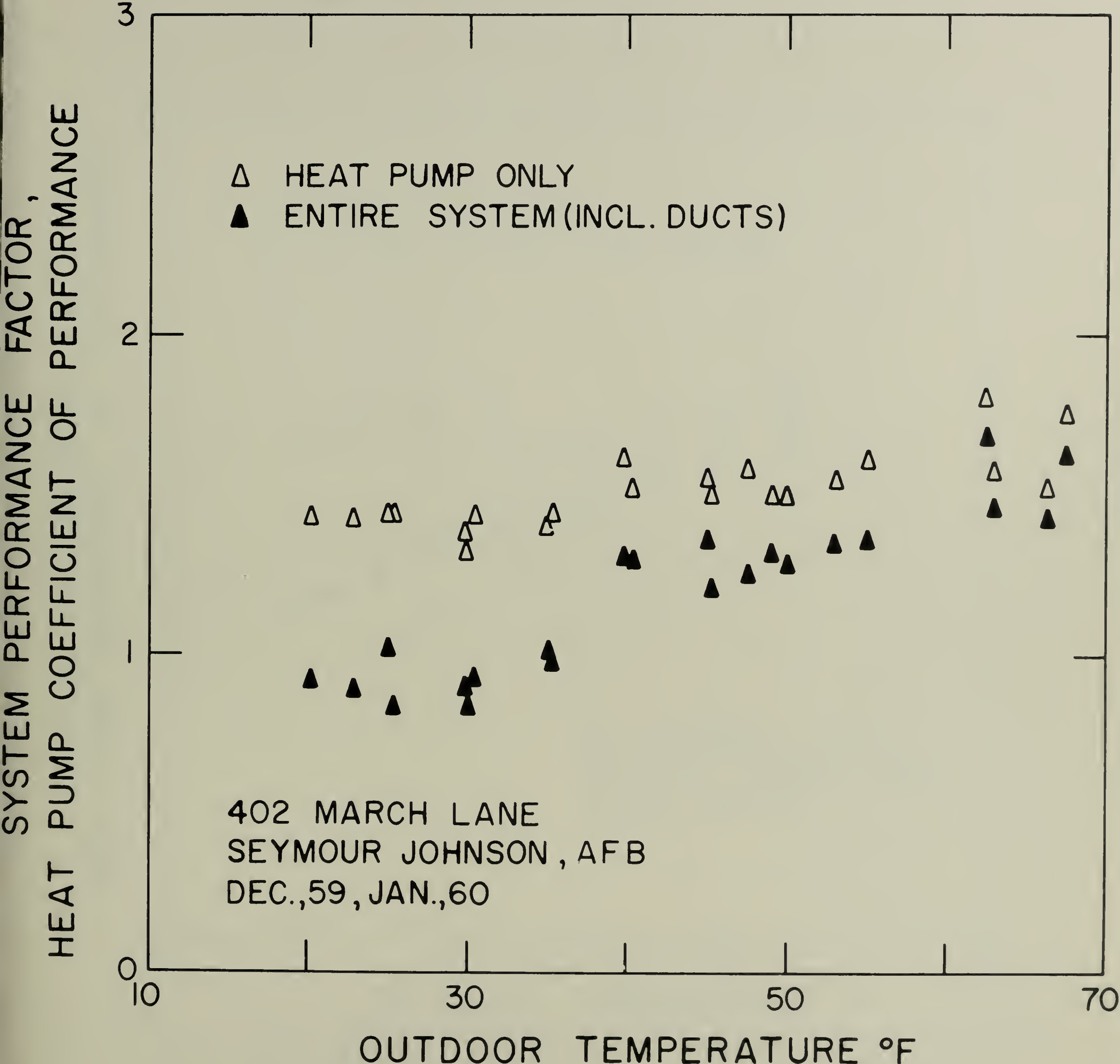

Fig. 31. Heat Pump Coefficient of Performance and System Performance Factor for the Type A Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

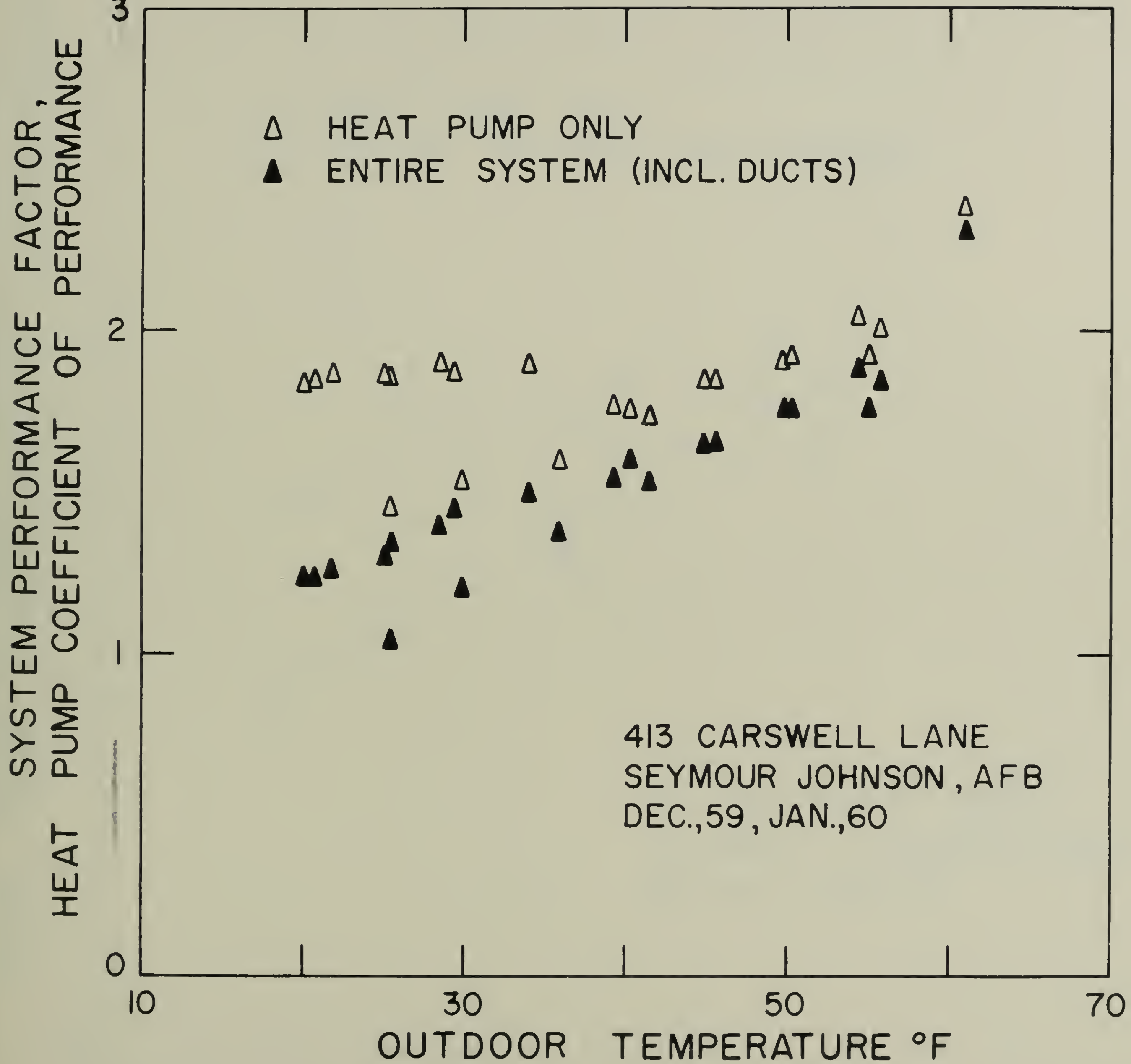

Fig. 32. Heat Pump Coefficient of Performance and System Performance Factor for the Type B Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

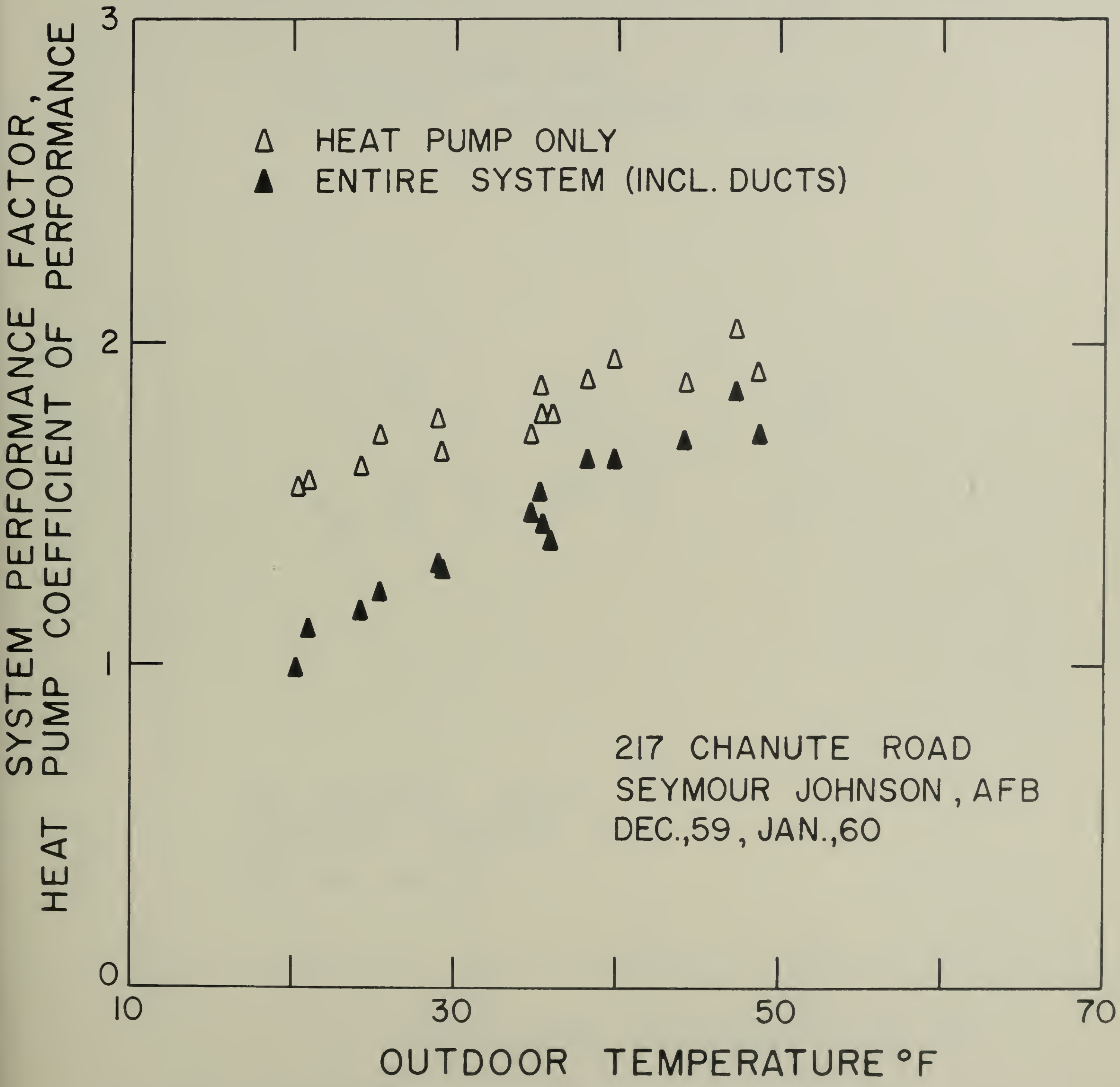

Fig. 33. Heat Pump Coefficient of Performance and System Performance Factor for the Type C Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

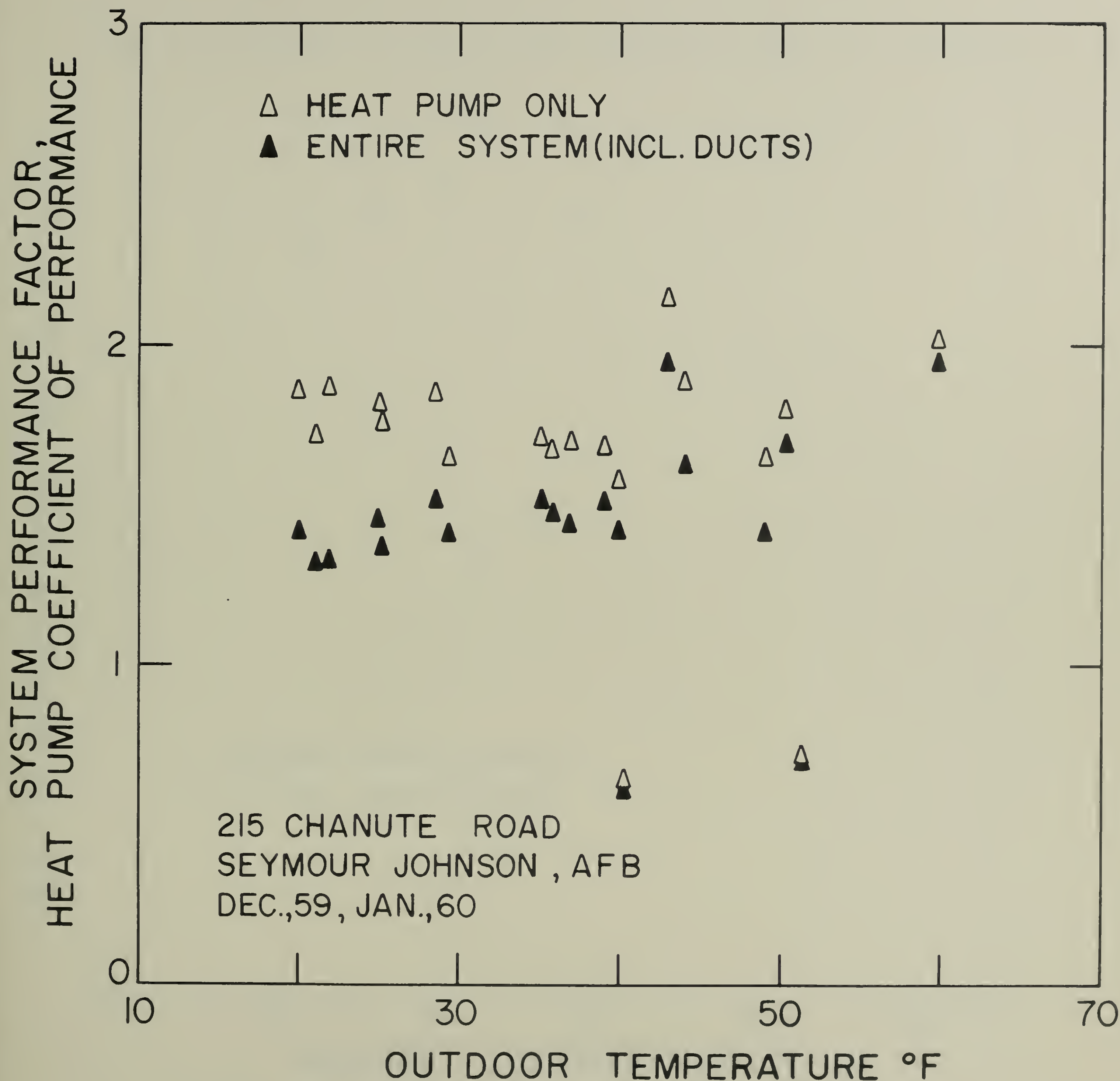

Fig. 34. Heat Pump Coefficient of Performance and System Performance Factor for the Type D Dwelling, Seymour Johnson AFB, for a Range of Outdoor Temperature

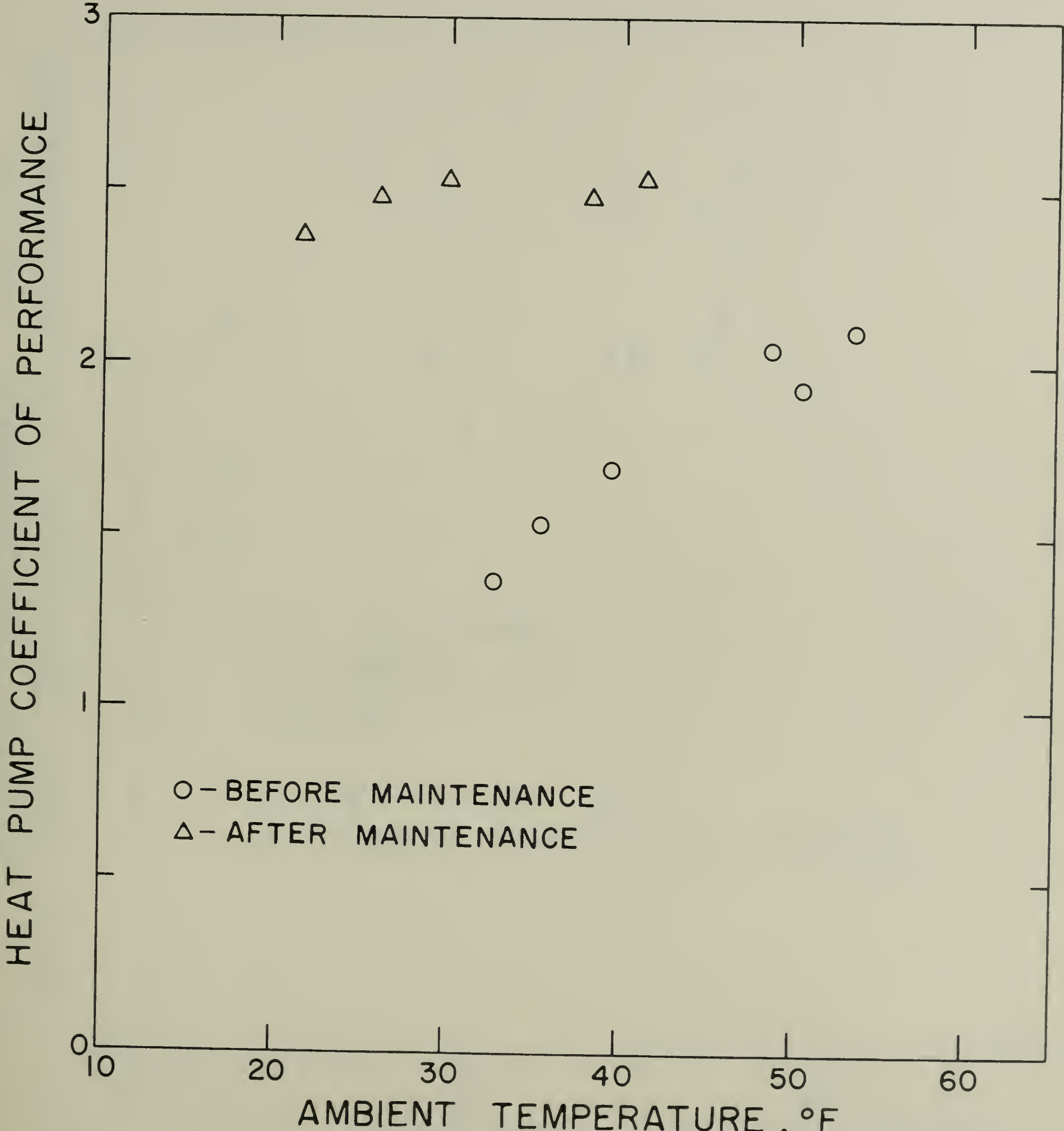

Fig. 35. Heat Pump Coefficient of Performance for the Type E House, Seymour Johnson AFB, for a Range of Outdoor Temperature

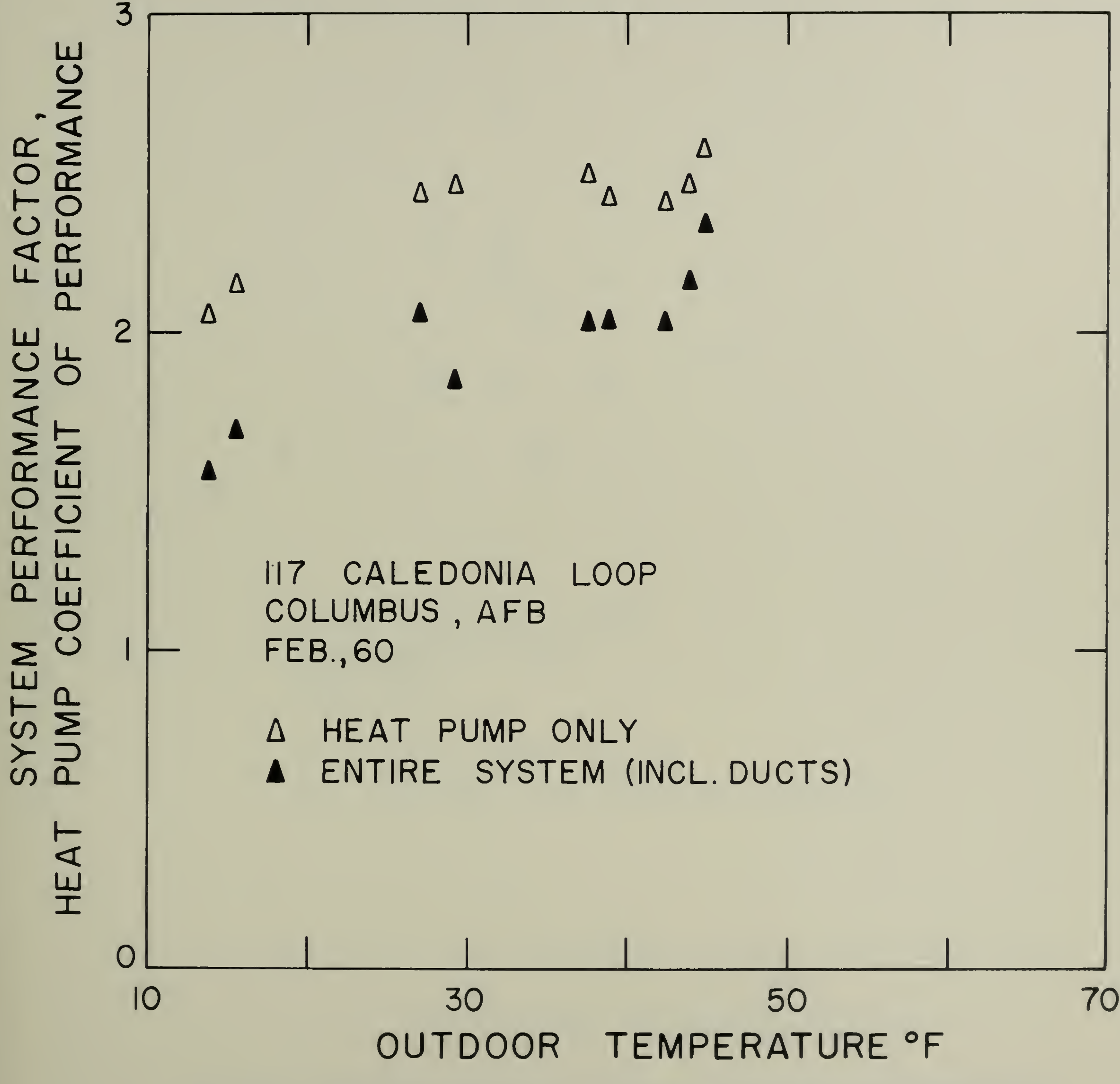

Fig. 36. Heat Pump Coefficient of Performance and System Performance Factor for the Type A3D1 Dwelling at 117 Caledonia Loop, Columbus AFB, for a Range of Outdoor Temperature

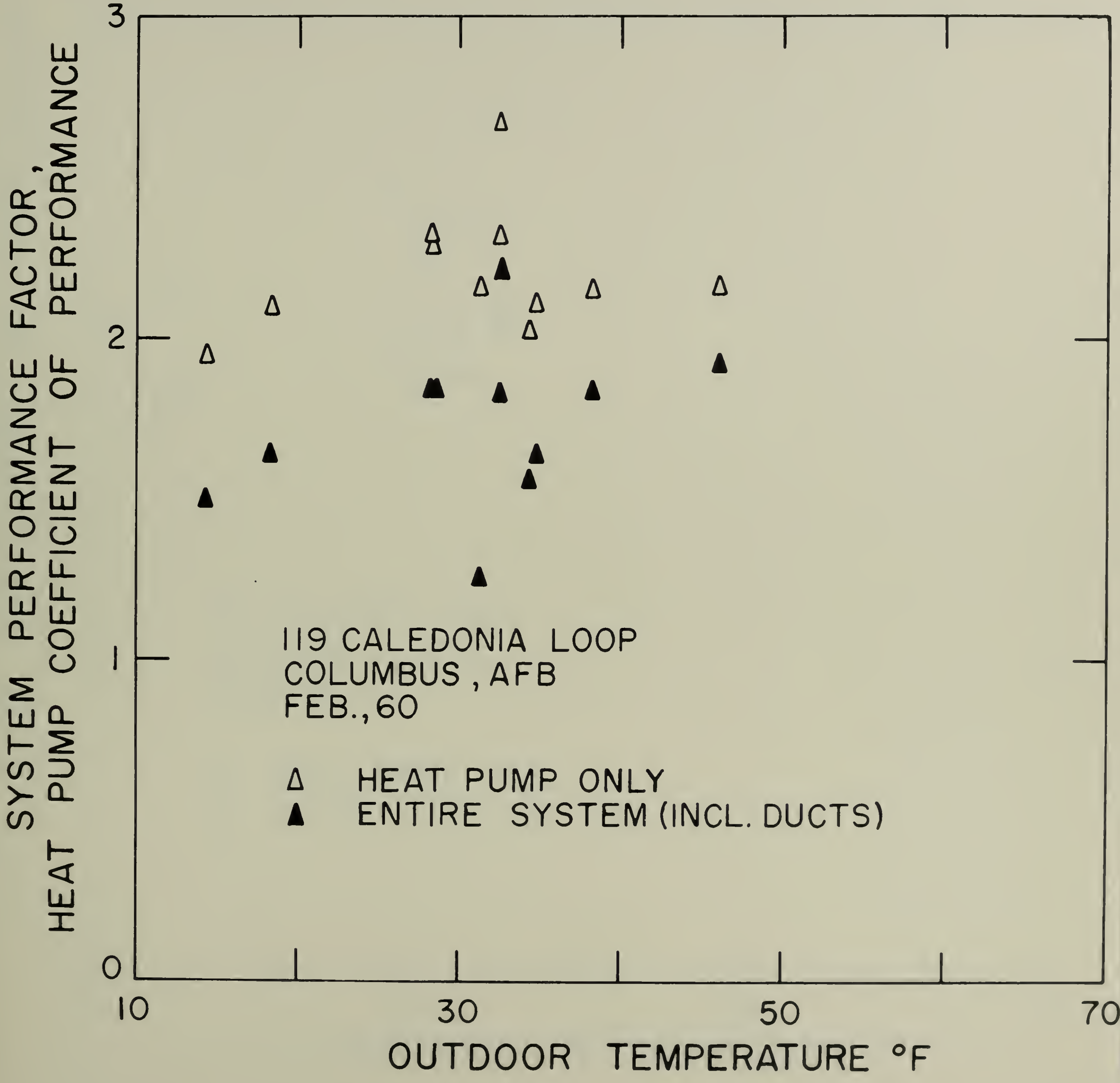

Fig. 37. Heat Pump Coefficient of Performance and System Performance Factor for the Type A3D1 Dwelling at 119 Caledonia Loop, Columbus AFB, for a Range of Outdoor Temperature

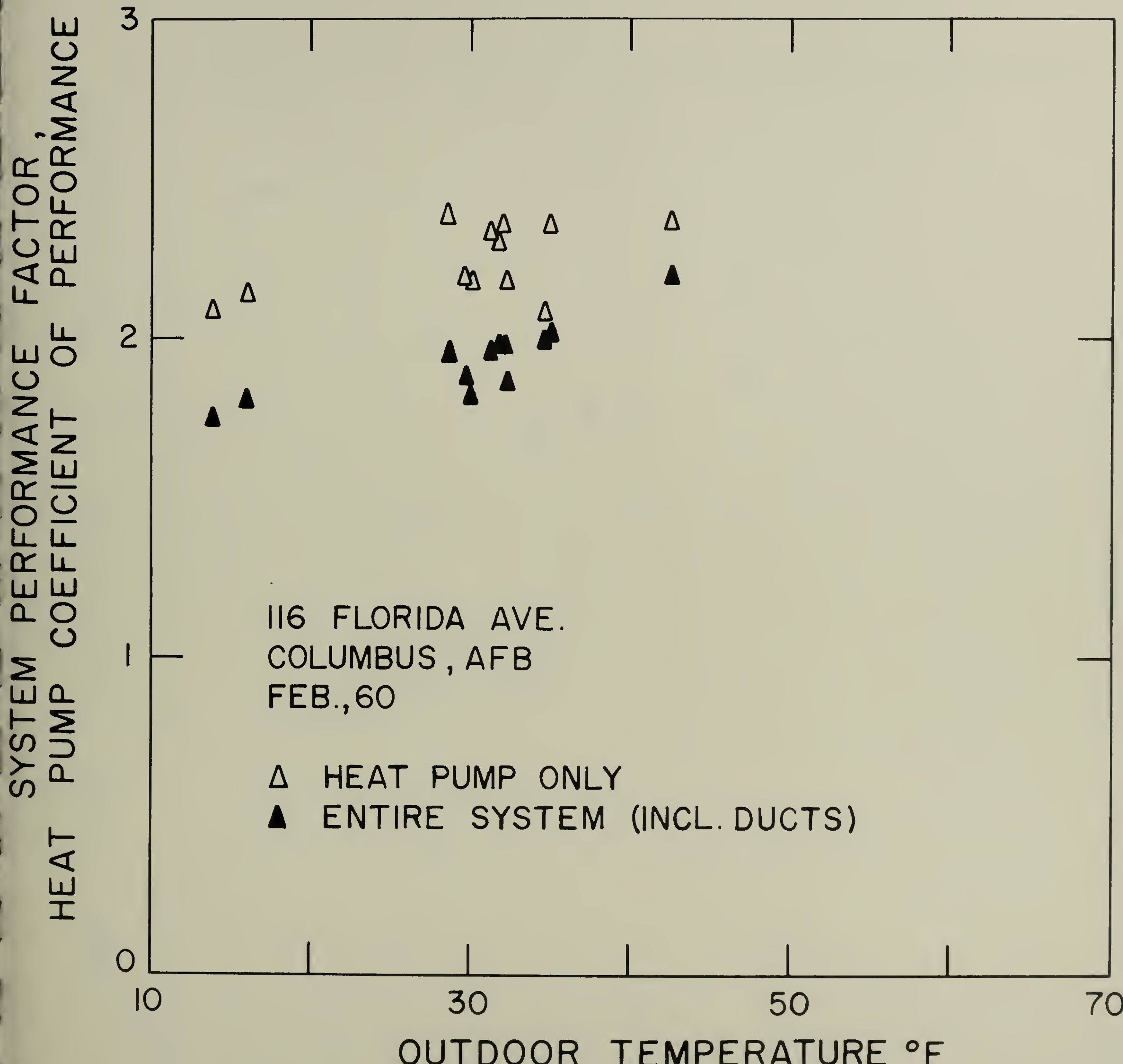

Fig. 38. Heat Pump Coefficient of Performance and System Performance Factor for the Type 03S1R House, Columbus AFB, for a Range of Outdoor Temperature

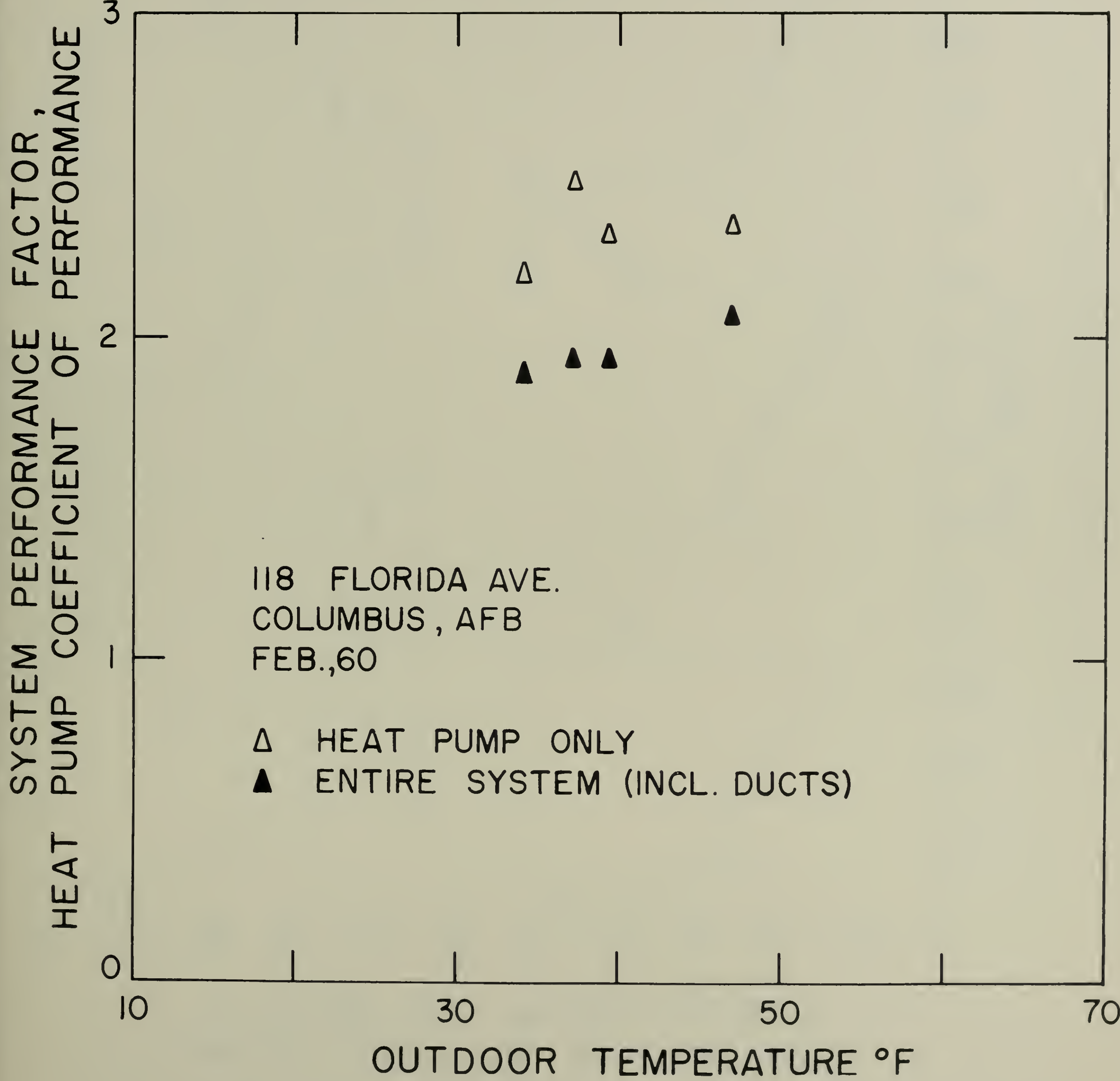

Fig. 39. Heat Pump Coefficient of Performance and System Performance Factor for the Type 03S3 House, Columbus AFB, for a Range of Outdoor Temperature

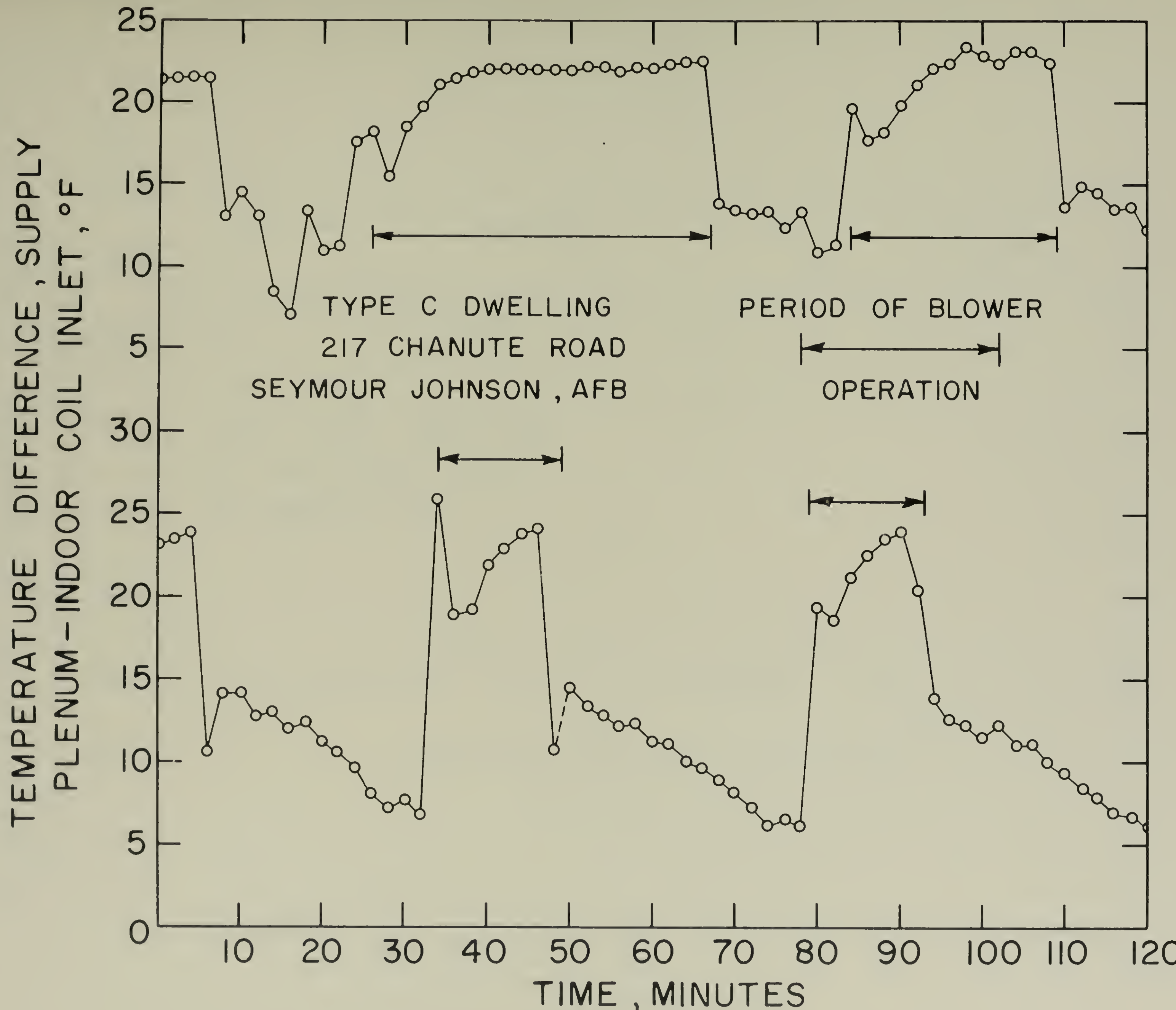

Fig. 40. Pattern of Temperature Rise of Warmed Air Produced by the Heat Pump in the Type C Dwelling During Long (Upper Curve) and Short (Lower Curve) Running Periods

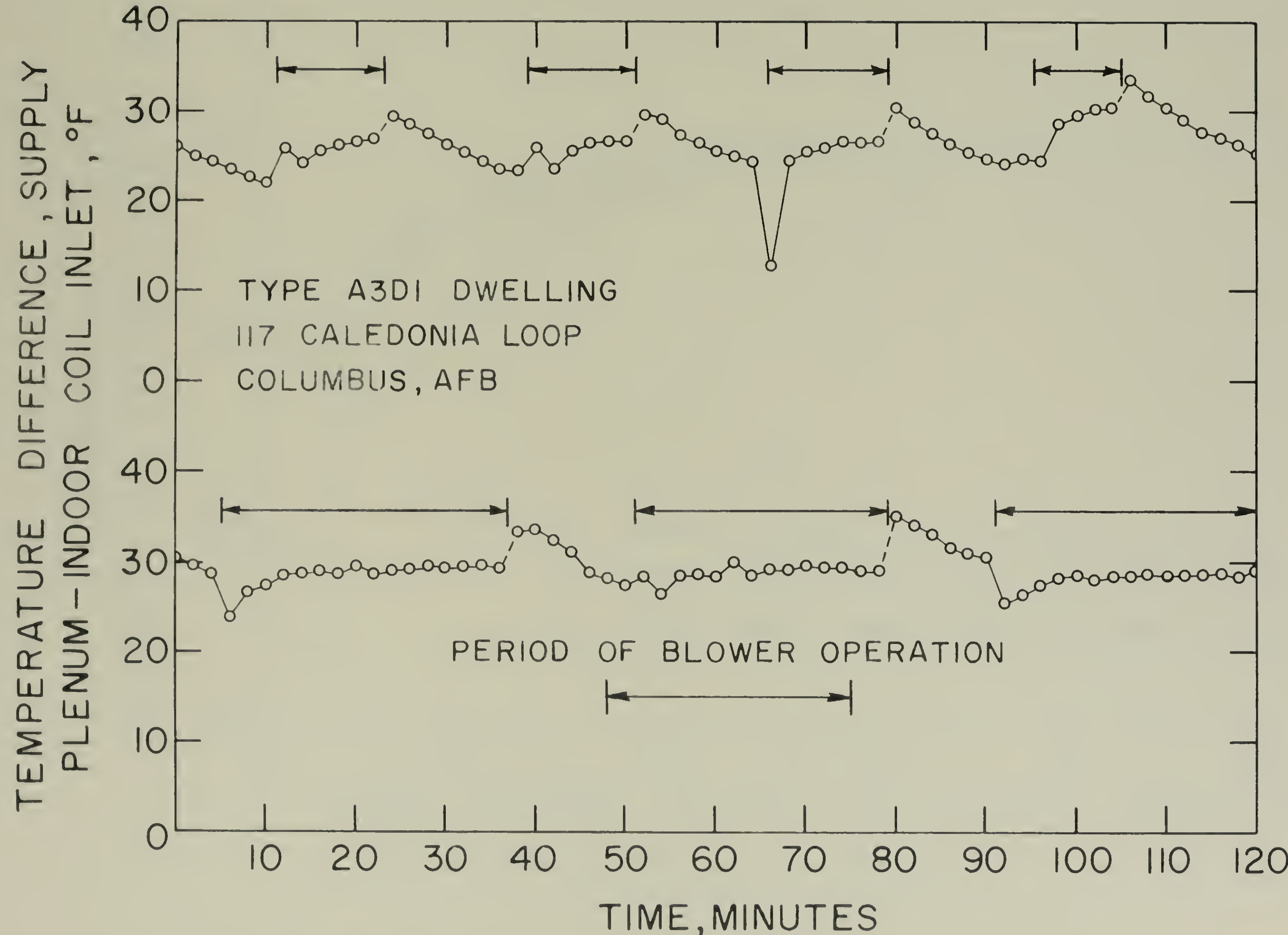

Fig. 41. Pattern of Temperature Rise of Warmed Air Produced by the Heat Pump in a Type A3D1 Dwelling During 2-Cylinder Operation (Lower Curve) and 3-Cylinder Operation (Upper Curve)

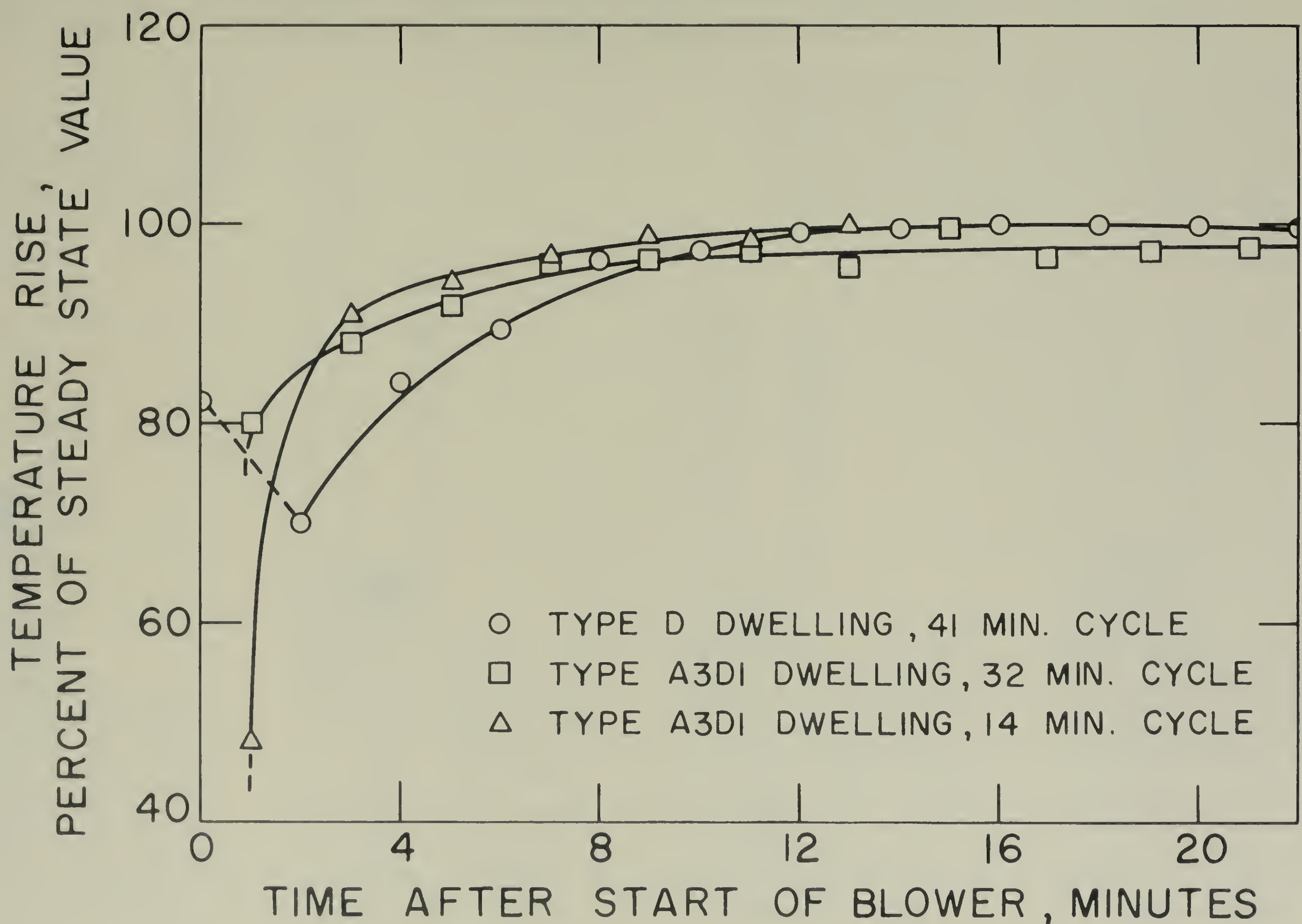

Fig. 42. Ratio of Temperature Rise of Warmed Air to Steady State Temperature Rise Plotted Against Time after Start of a Heating and Blower Cycle

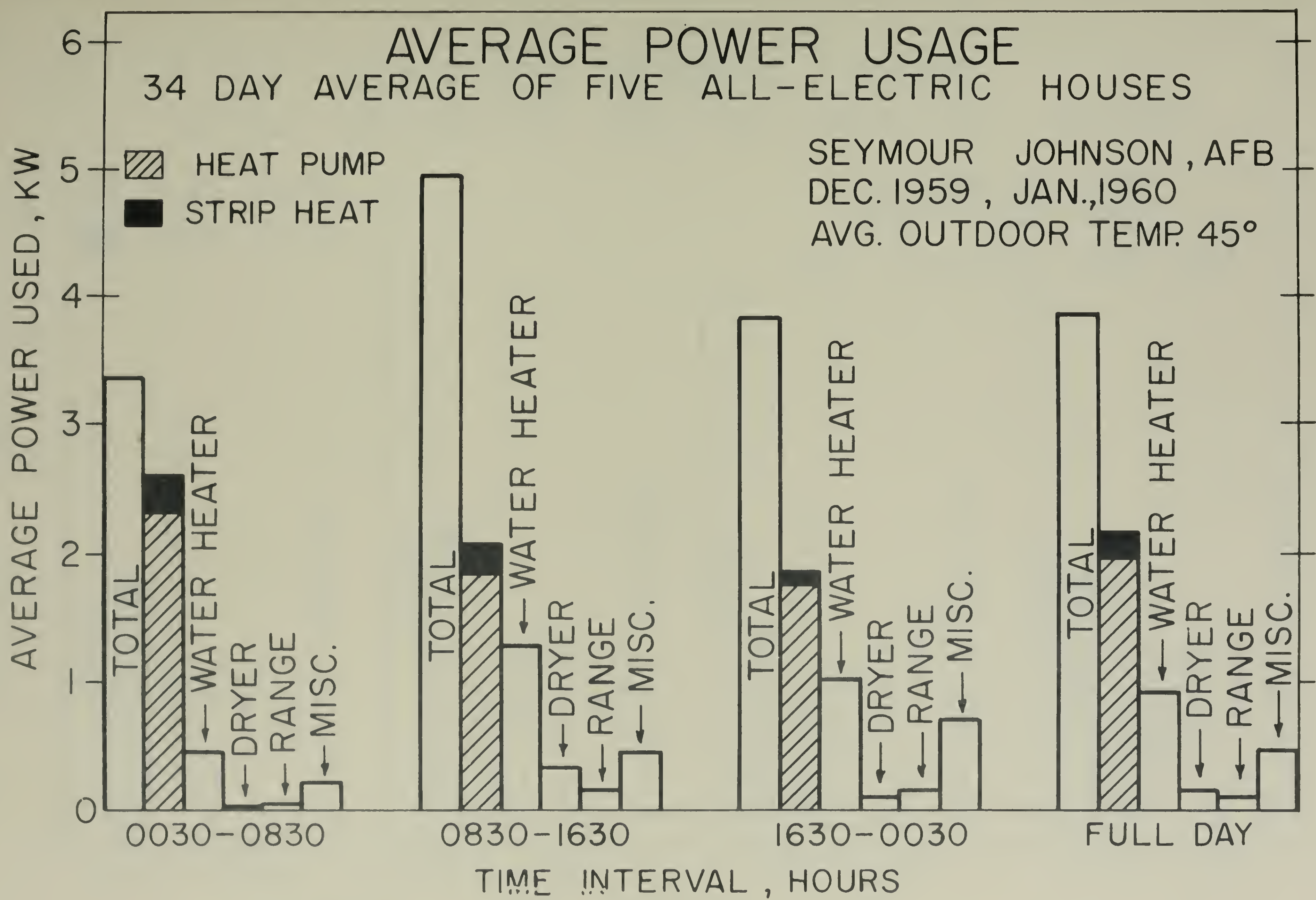

Fig. 43. Bar Graph Showing the 34-Day Average Power Used in the Five Sample Dwellings at Seymour Johnson AFB by Each Component of the Load and for the House As a Whole During Three Portions of the Day, and for the Entire Day

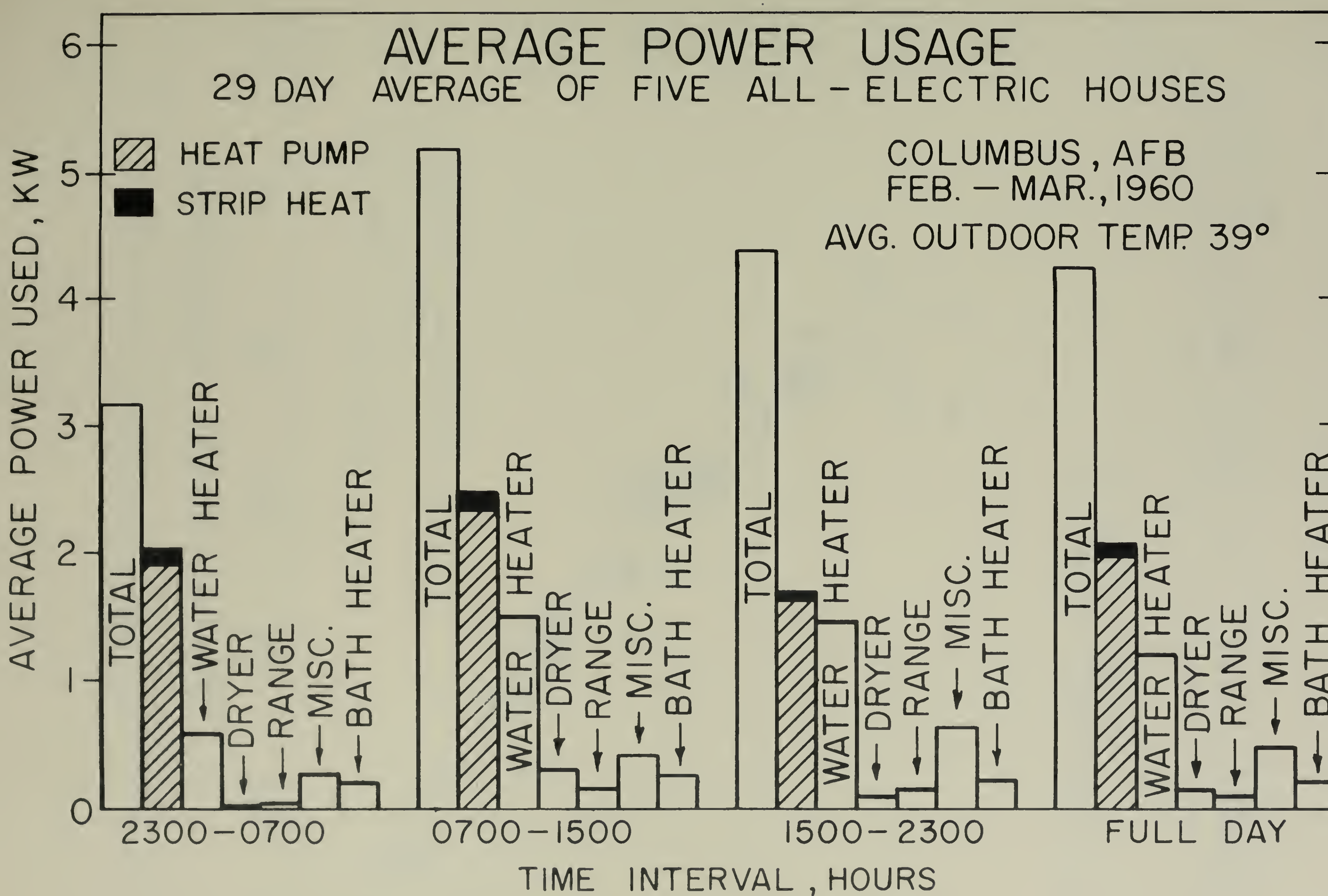

Fig. 44. Bar Graph Showing the 29-Day Average Power Used in the Five Sample Dwellings at Columbus AFB by Each Component of the Load and for the House as a Whole During Three Portions of the Day and for the Entire Day

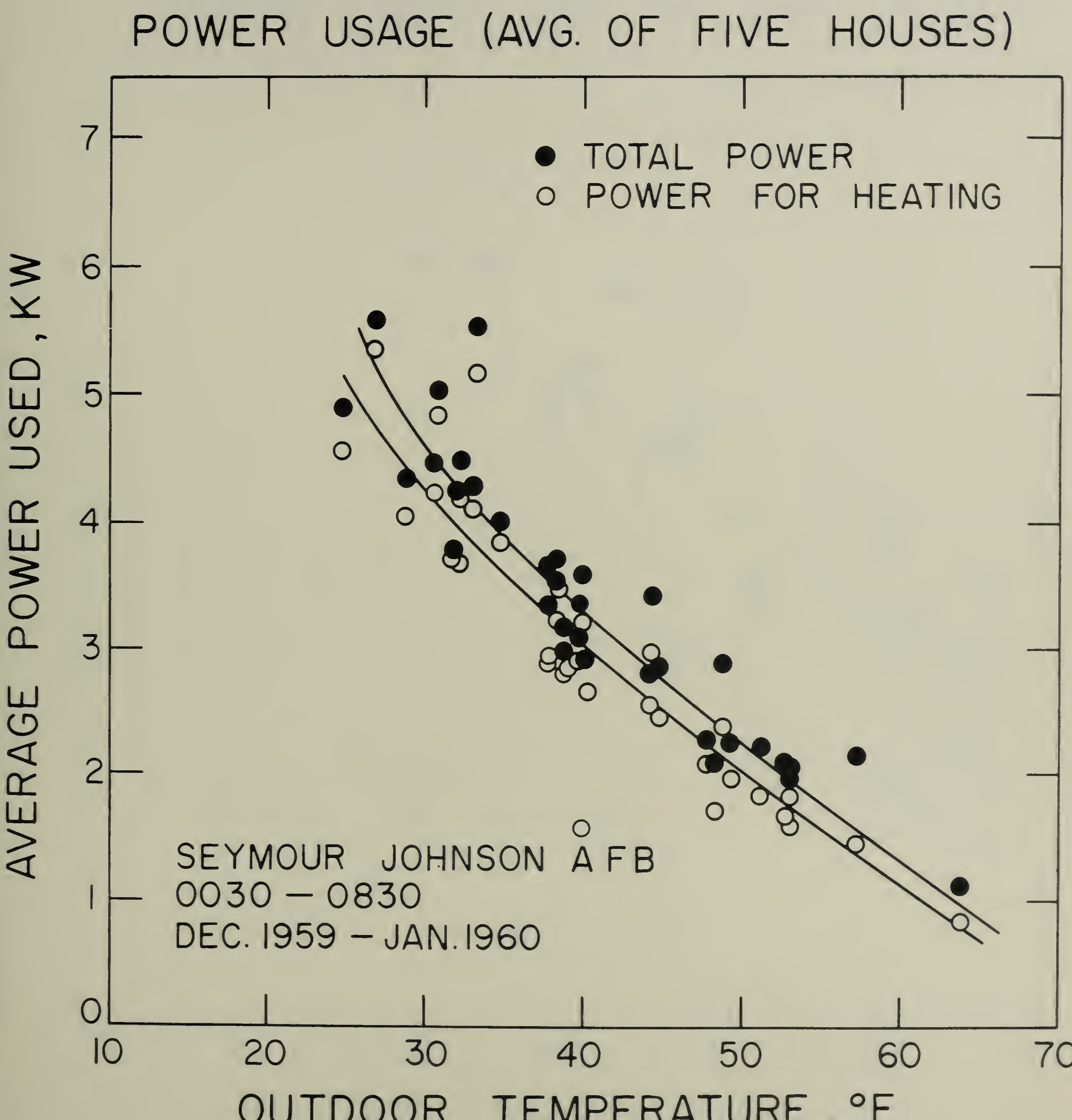

Fig. 45. Average Power Used for Heating and for All Purposes During the Hours 0030 to 0830 in the Five Sample Houses at Seymour Johnson AFB, for a Range of Outdoor Temperature

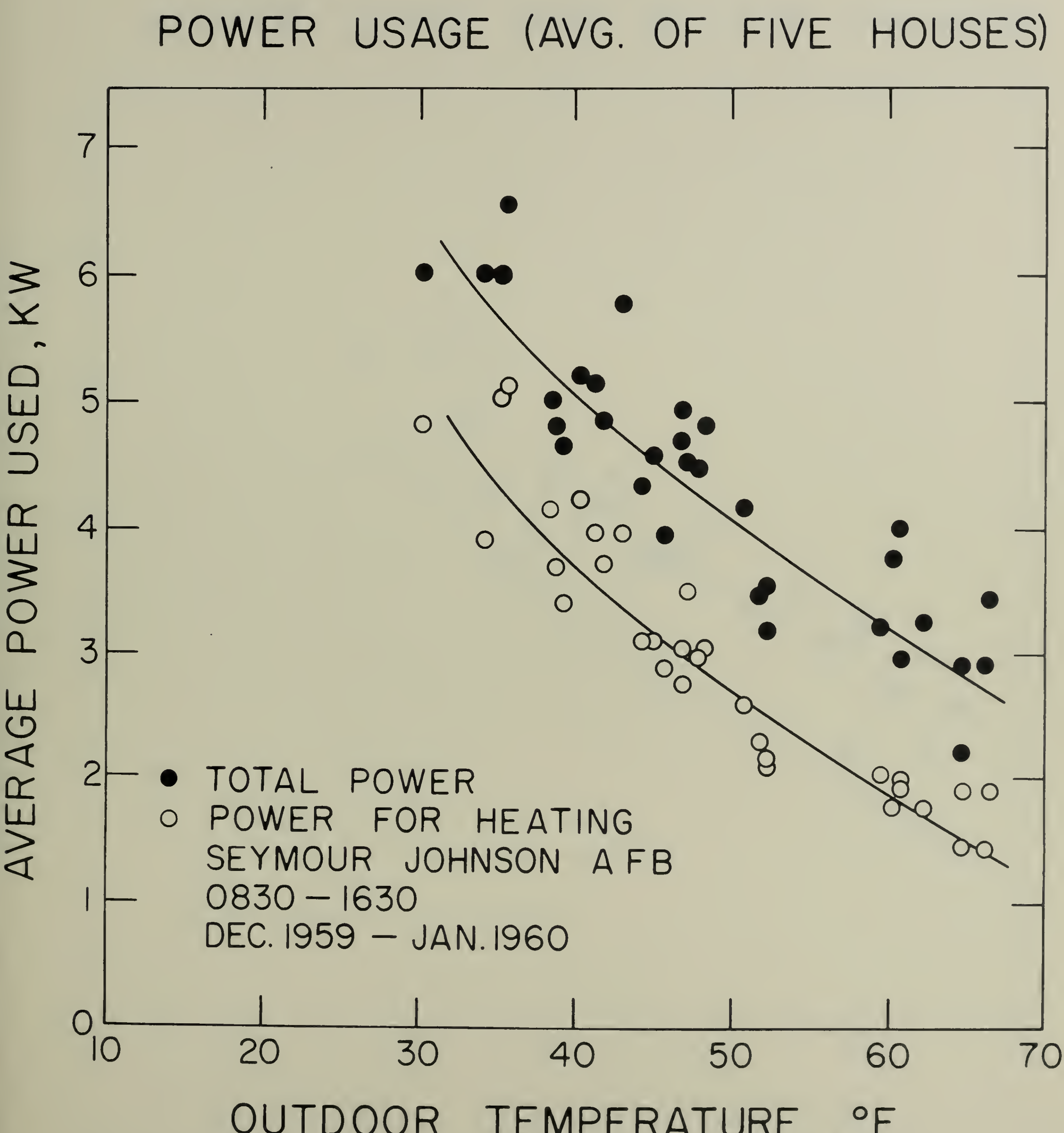

Fig. 46. Average Power Used for Heating and for All Purposes During the Hours 0830 to 1630 in the Five Sample Houses at Seymour Johnson AFB for a Range of Outdoor Temperature

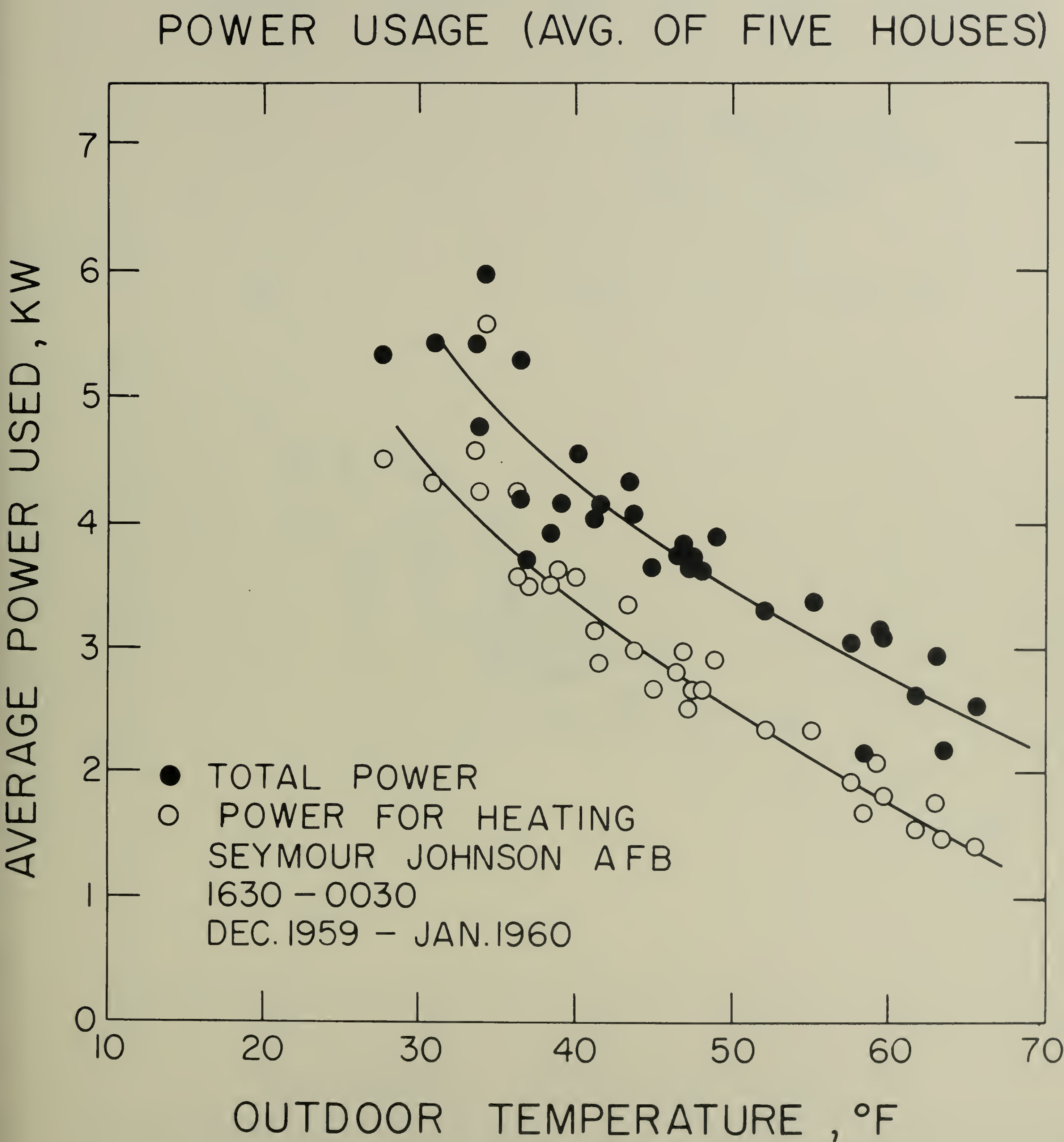

Fig. 47. Average Power Used for Heating and for All Purposes During the Hours 1630 to 0030 in the Five Sample Houses at Seymour Johnson AFB for a Range of Outdoor Temperature

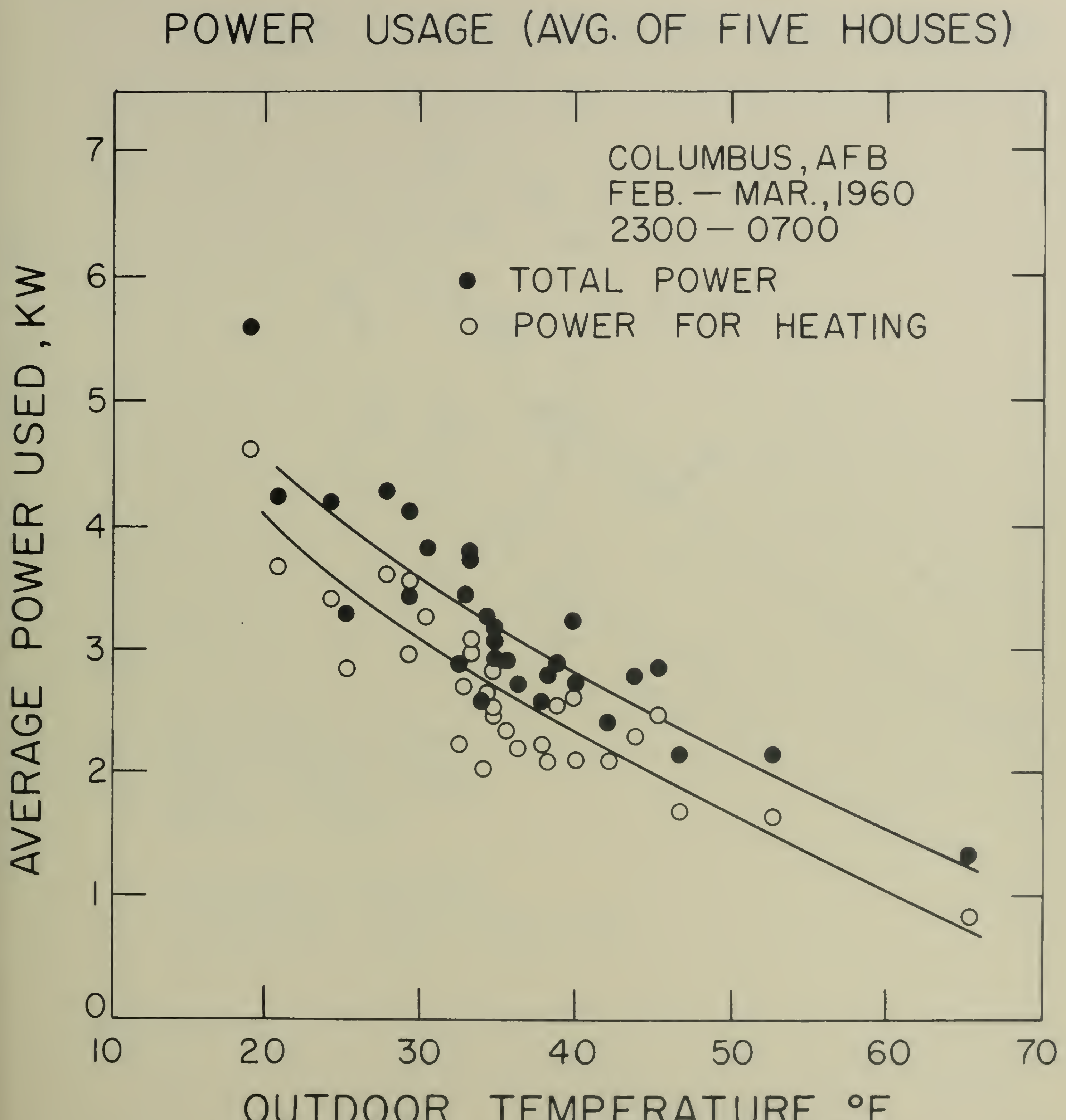

Fig. 48. Average Power Used for Heating and for All Purposes During the Hours 2300 to 0700 in the Five Sample Houses at Columbus AFB for a Range of Outdoor Temperature

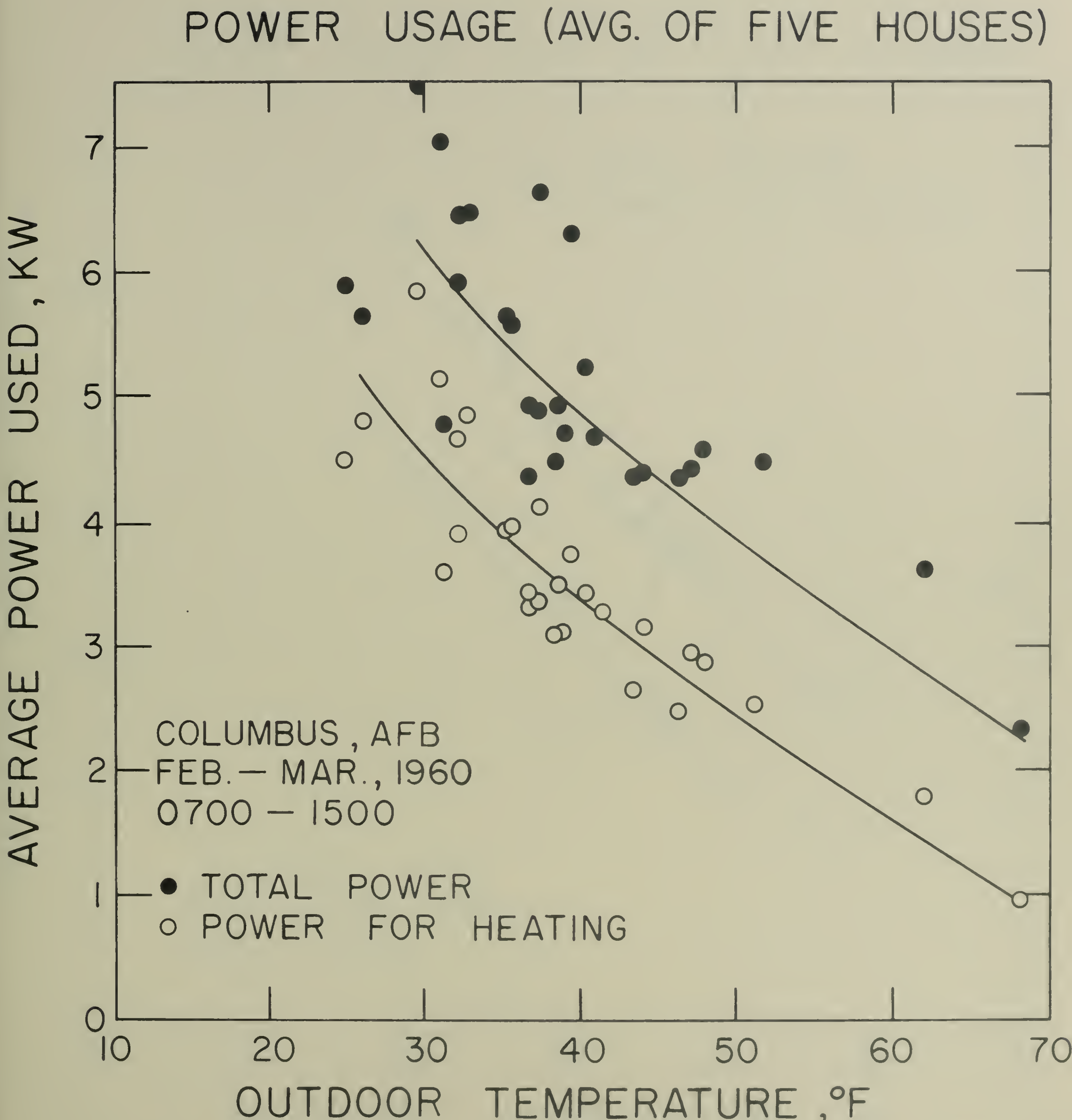

Fig. 49. Average Power Used for Heating and for All Purposes During the Hours 0700 to 1500 in the Five Sample Houses at Columbus AFB, for a Range of Outdoor Temperature

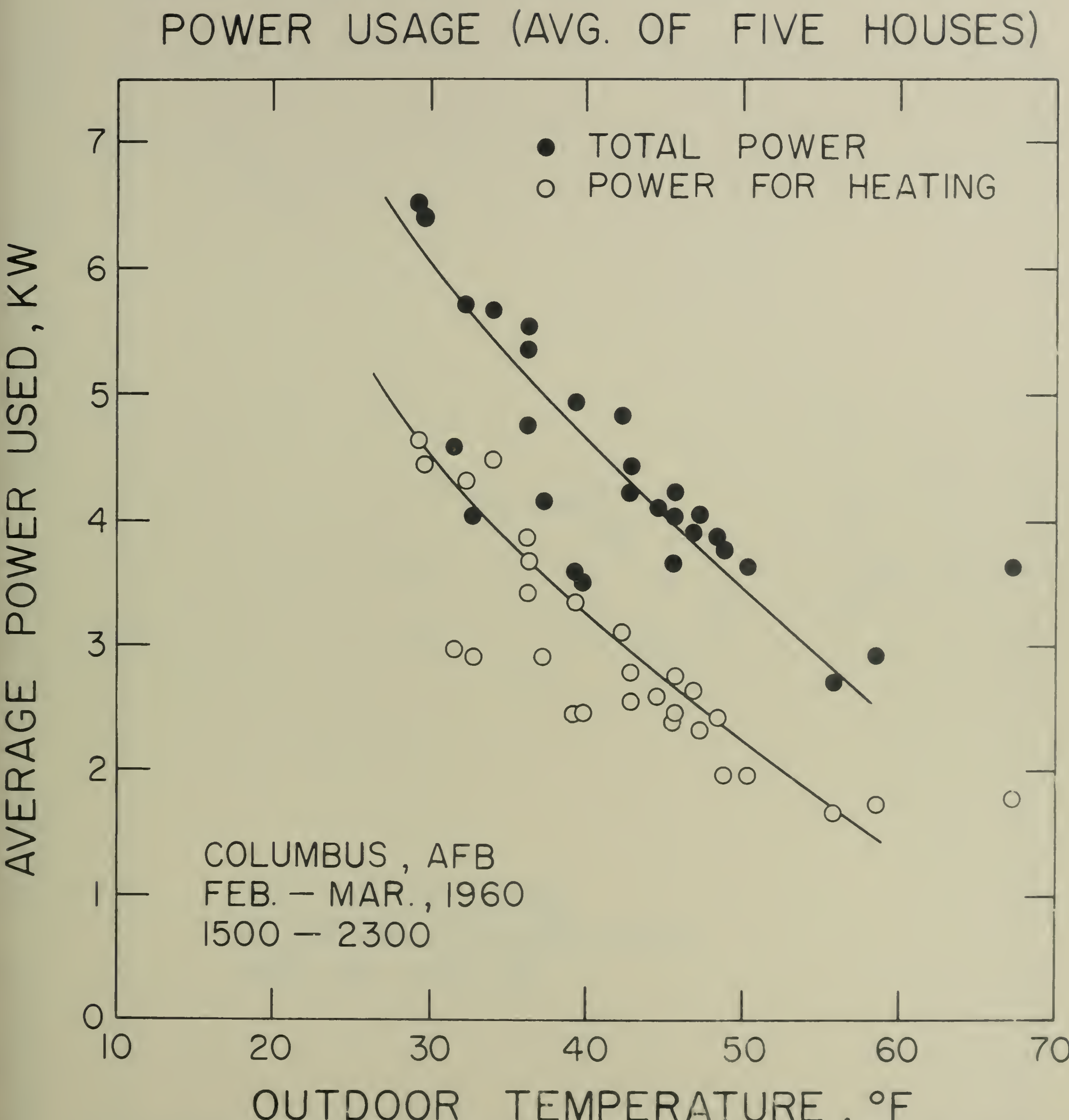

Fig. 50. Average Power Used for Heating and for All Purposes During the Hours 1500 to 2300 in the Five Sample Houses at Columbus AFB, for a Range of Outdoor Temperature

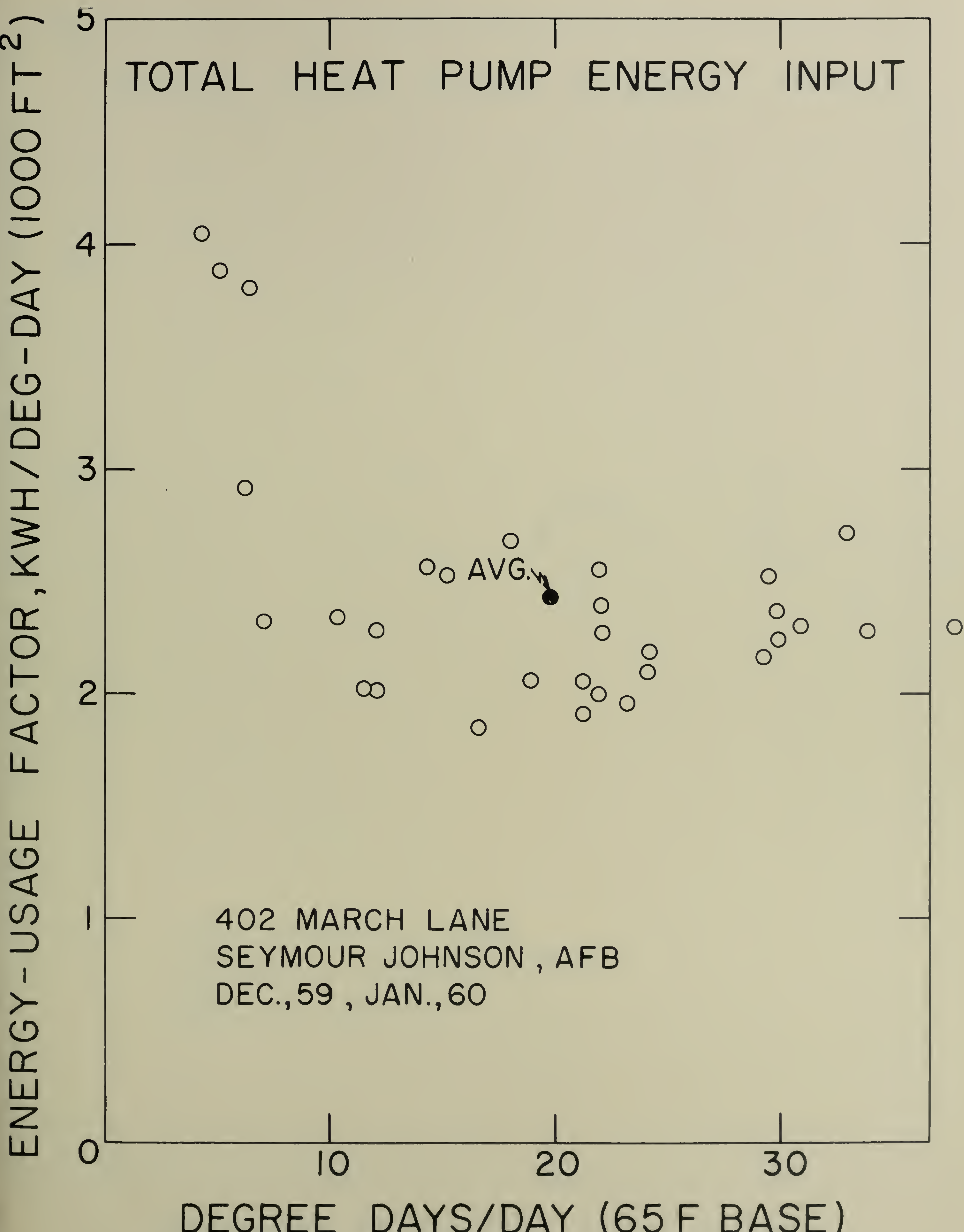

Fig. 51. The Energy-Usage Factor of the Heat Pump Unit in the Type A Dwelling, Seymour Johnson AFB, for a Range of Degree Days per Day

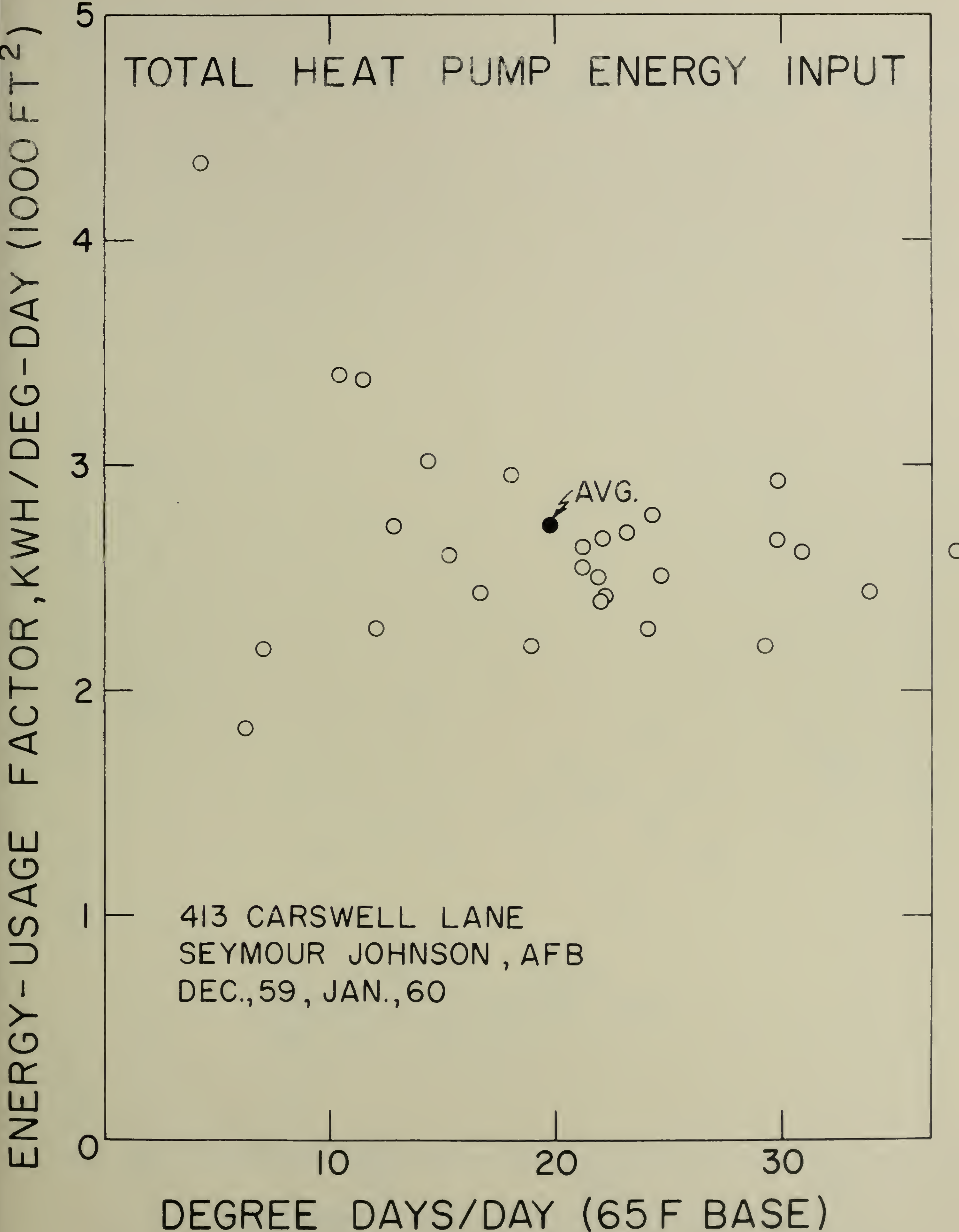

Fig. 52. The Energy-Usage Factor of the Heat Pump Unit in the Type B Dwelling, Seymour Johnson AFB, for a Range of Degree Days per Day

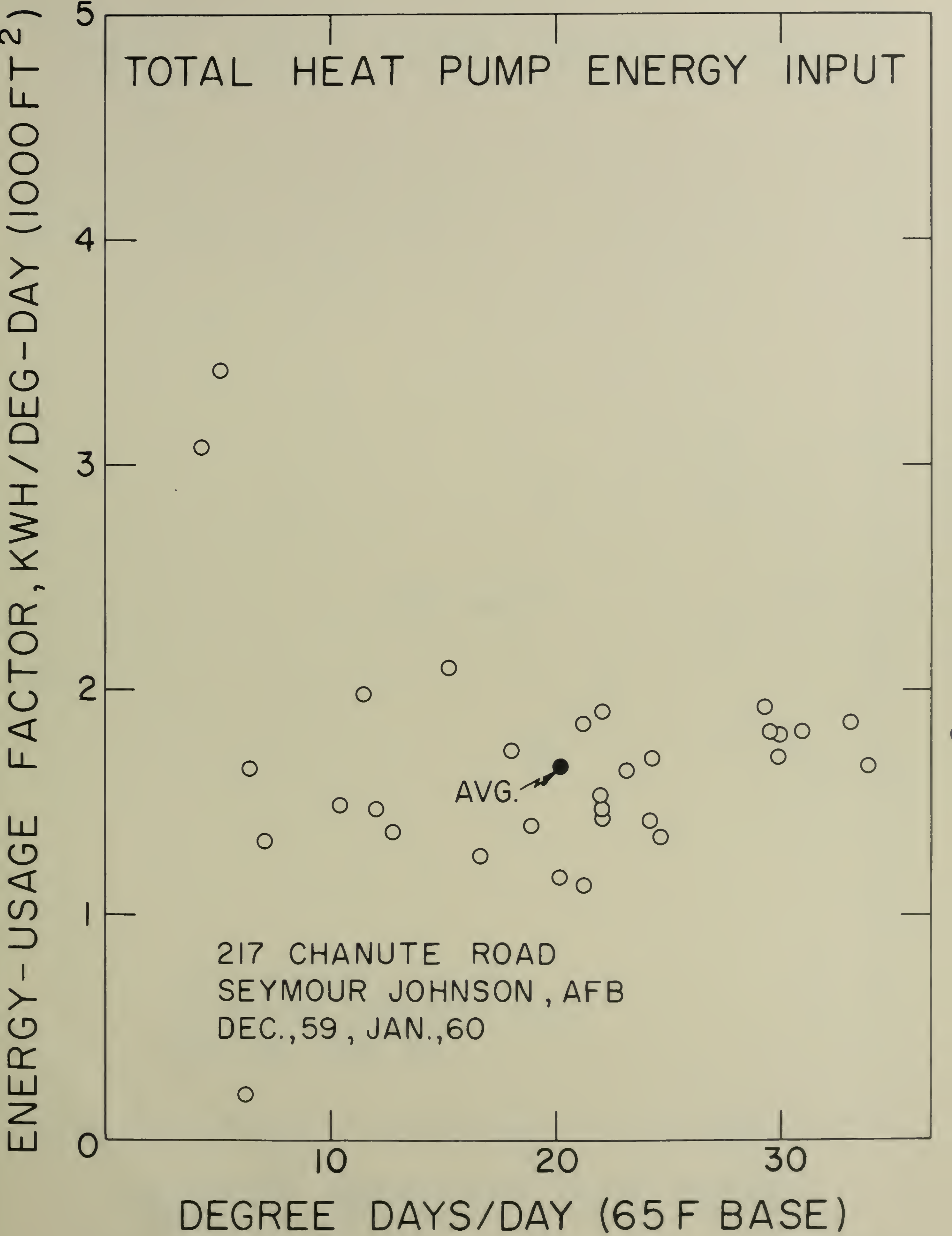

Fig. 53. The Energy-Usage Factor of the Heat Pump Unit in the Type C Dwelling, Seymour Johnson AFB, for a Range of Degree Days per Day

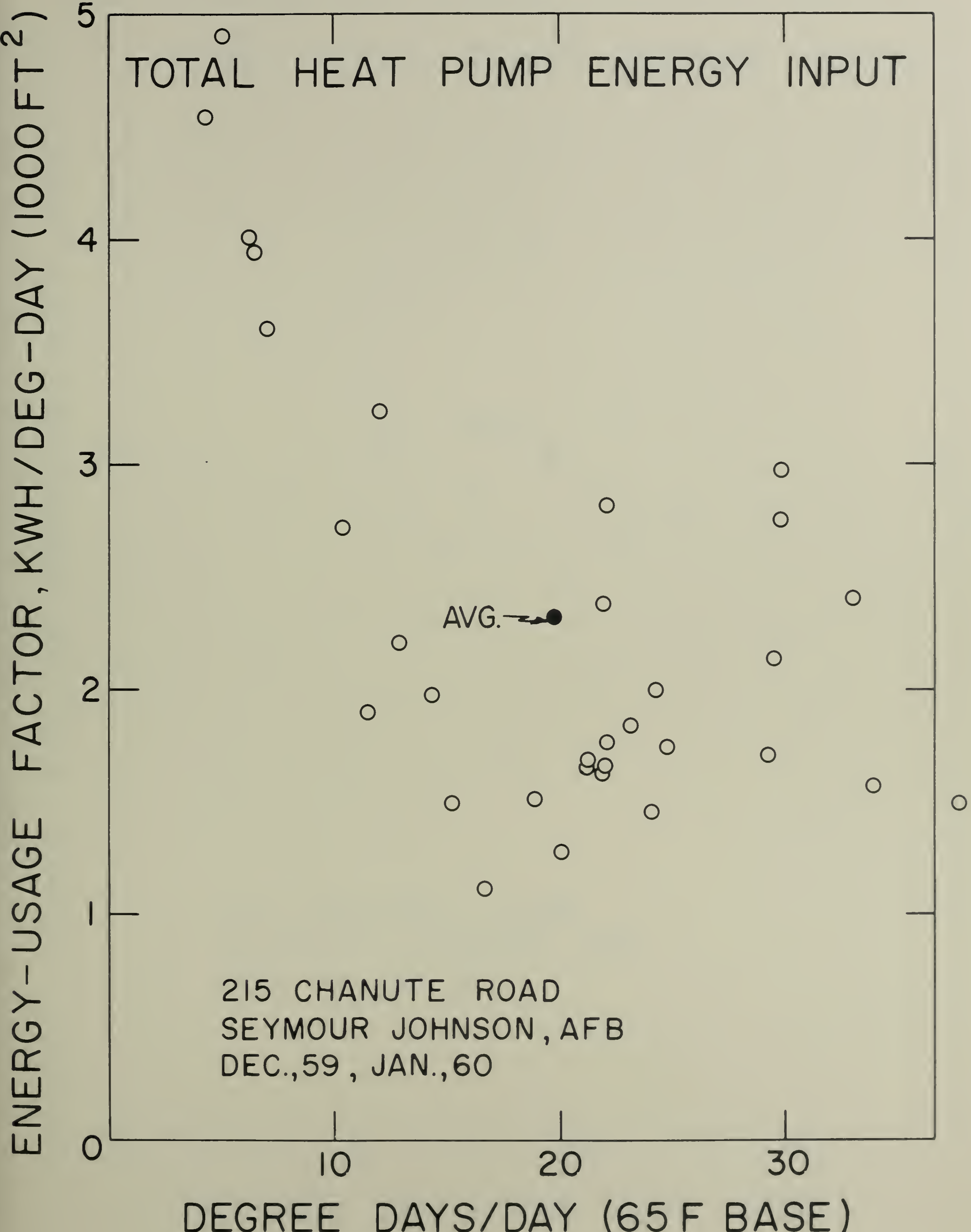

Fig. 54. The Energy-Usage Factor of the Heat Pump Unit in the Type D Dwelling, Seymour Johnson AFB, for a Range of Degree Days per Day

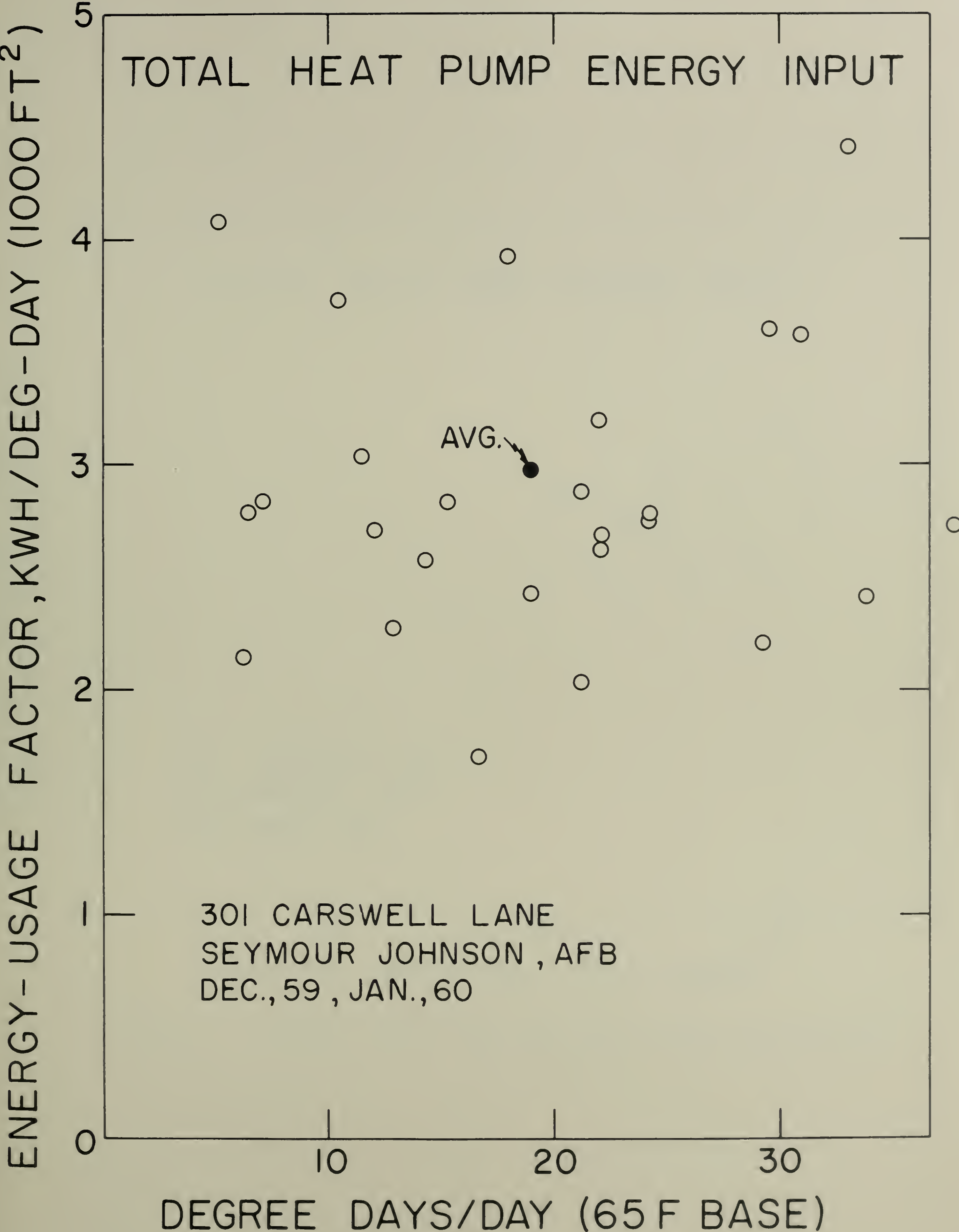

Fig. 55. The Energy-Usage Factor of the Heat Pump Unit in the Type E House, Seymour Johnson AFB, for a Range of Degree Days per Day

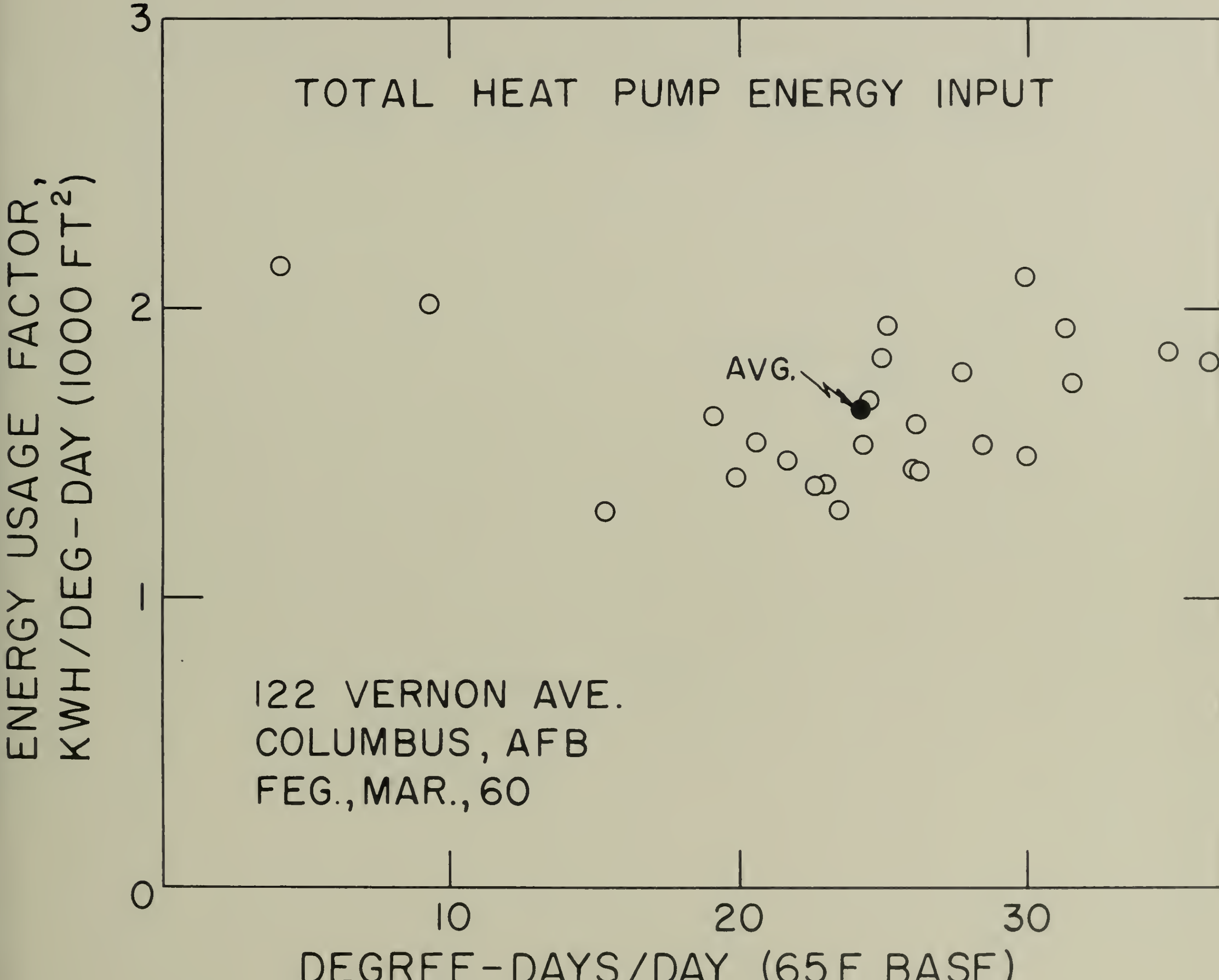

Fig. 56. The Energy-Usage Factor of the Heat Pump Unit in the Type A2D1 Dwelling, Columbus AFB, for a Range of Degree-Days per Day

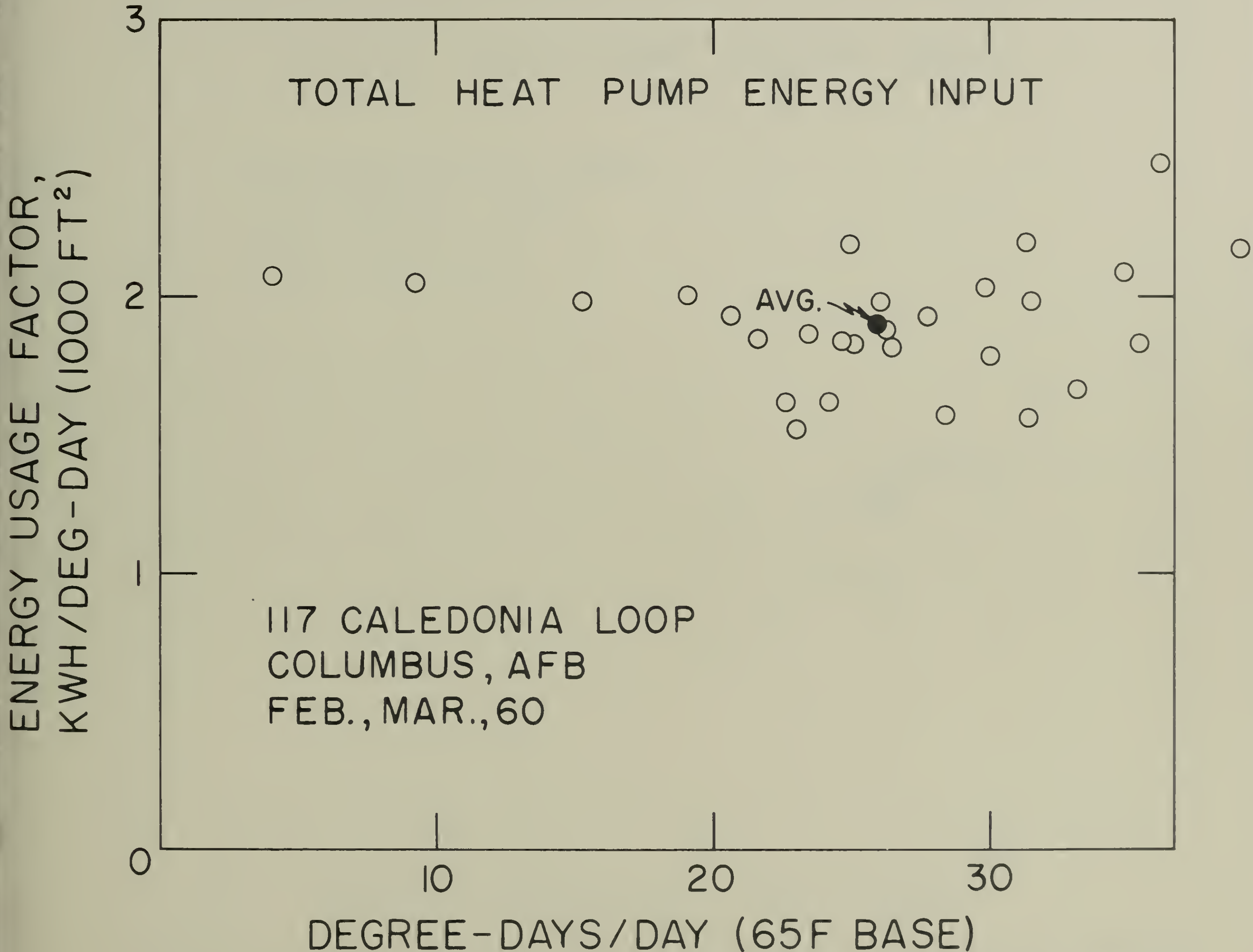

Fig. 57. The Energy-Usage Factor of the Heat Pump Unit in the Type A3D1 Dwelling at 117 Caledonia Loop, Columbus AFB, for a Range of Degree-Days per Day

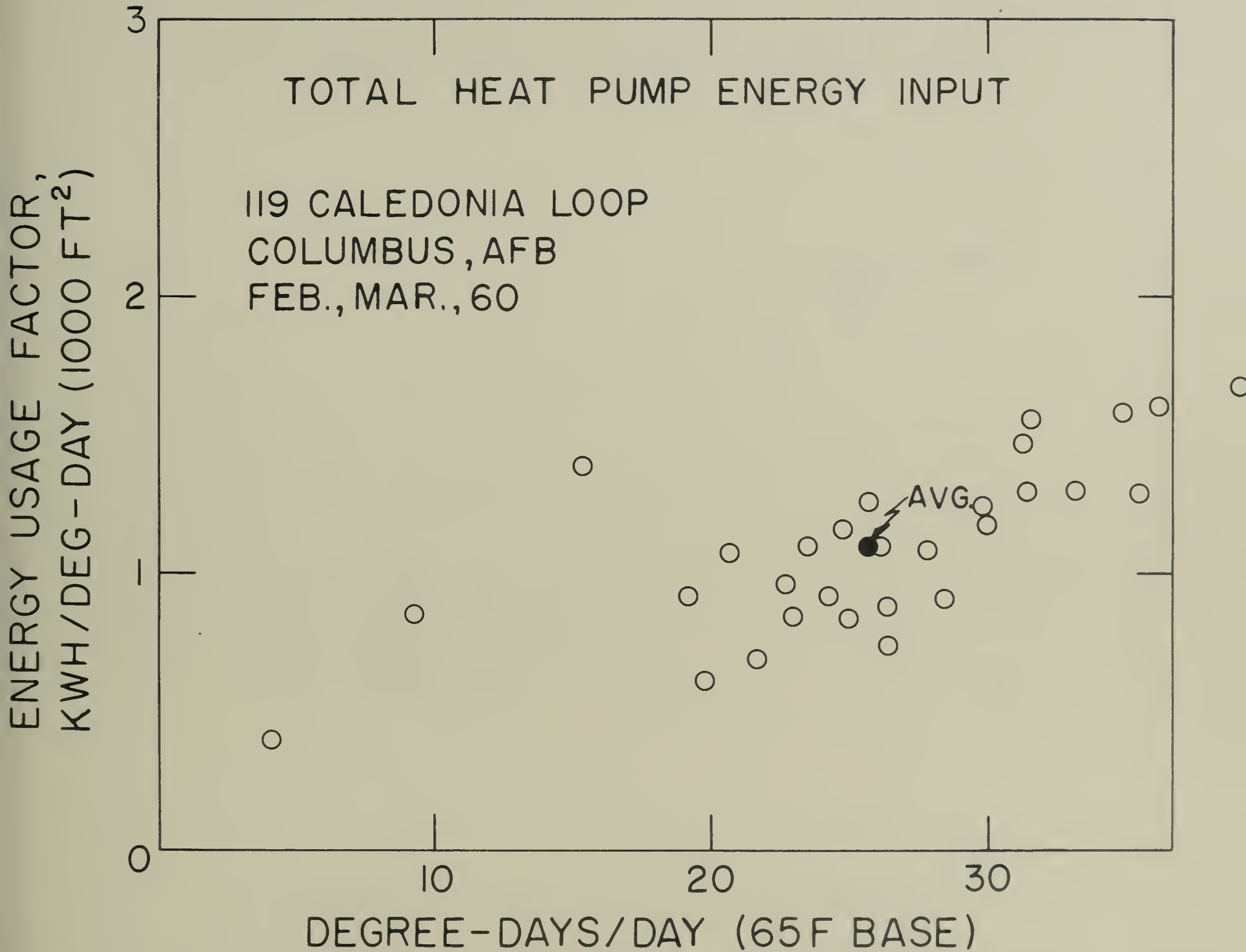

Fig. 58. The Energy-Usage Factor of the Heat Pump Unit in the Type A3D1 Dwelling at 119 Caledonia Loop, Columbus AFB, for a Range of Degree-Days per Day

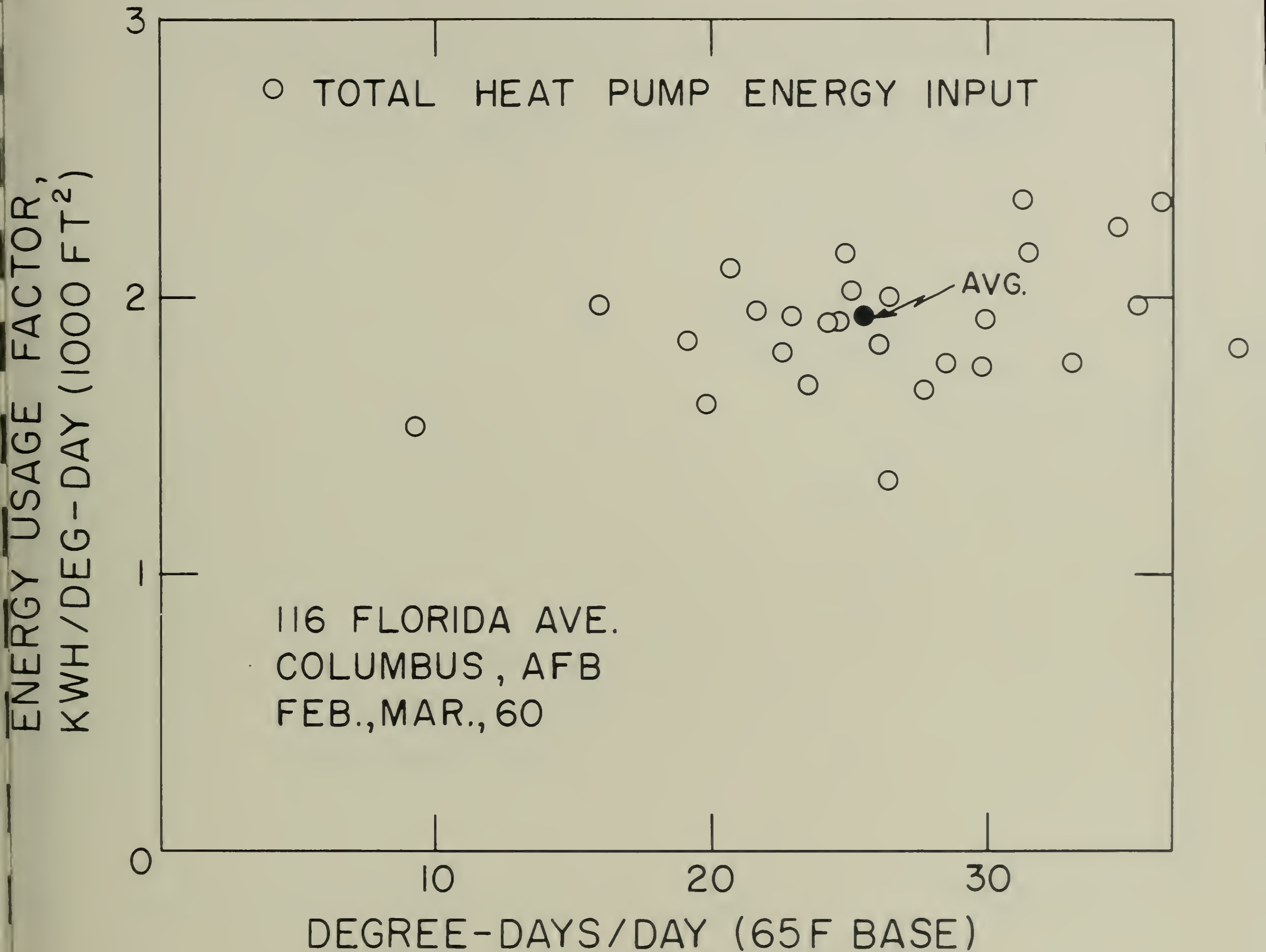

Fig. 59. The Energy-Usage Factor of the Heat Pump in the Type 03S1R House, Columbus AFB, for a Range of Degree-Days per Day

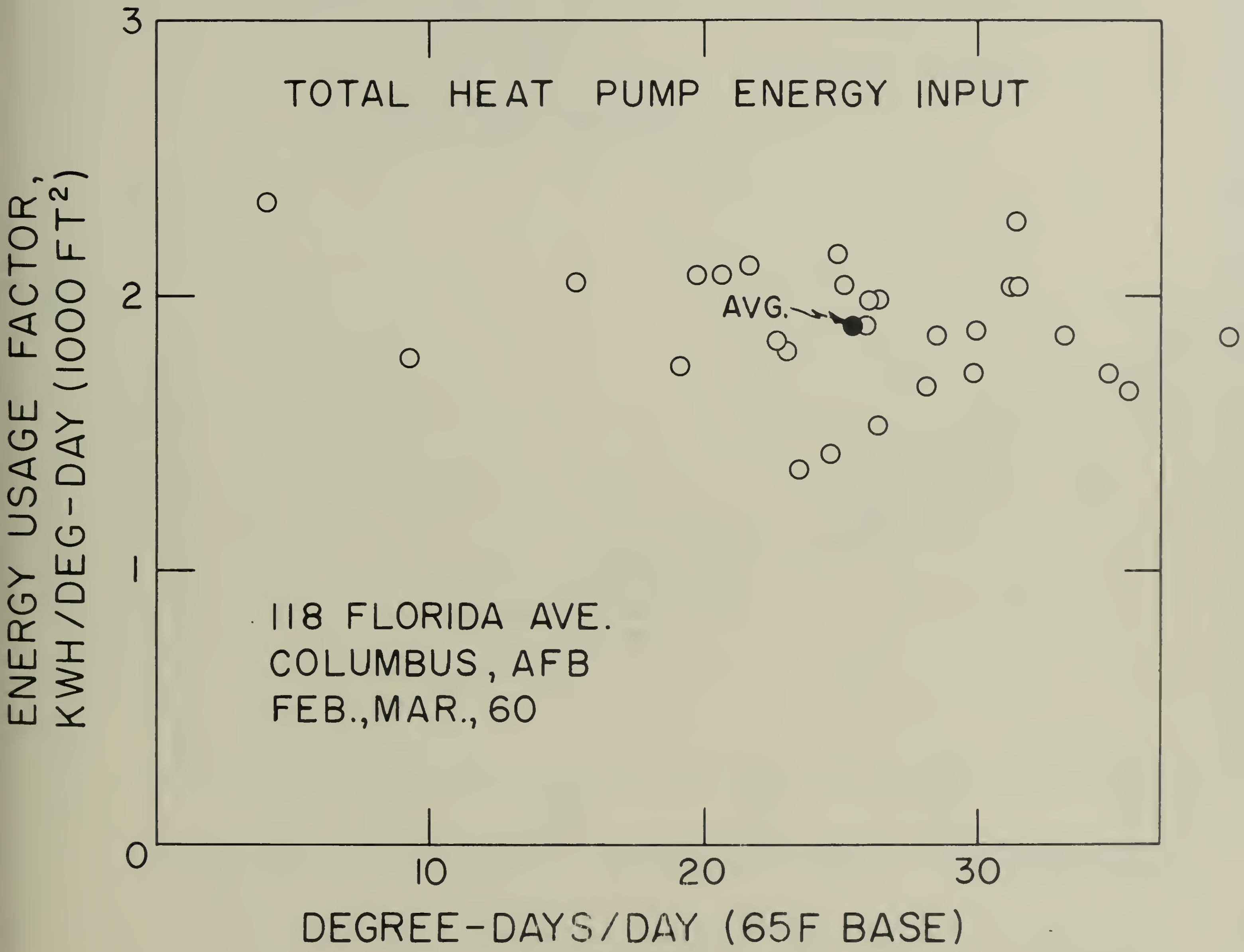

Fig. 60. The Energy-Usage Factor of the Heat Pump Unit in the Type 03S3 House, Columbus AFB, for a Range of Degree-Days per Day

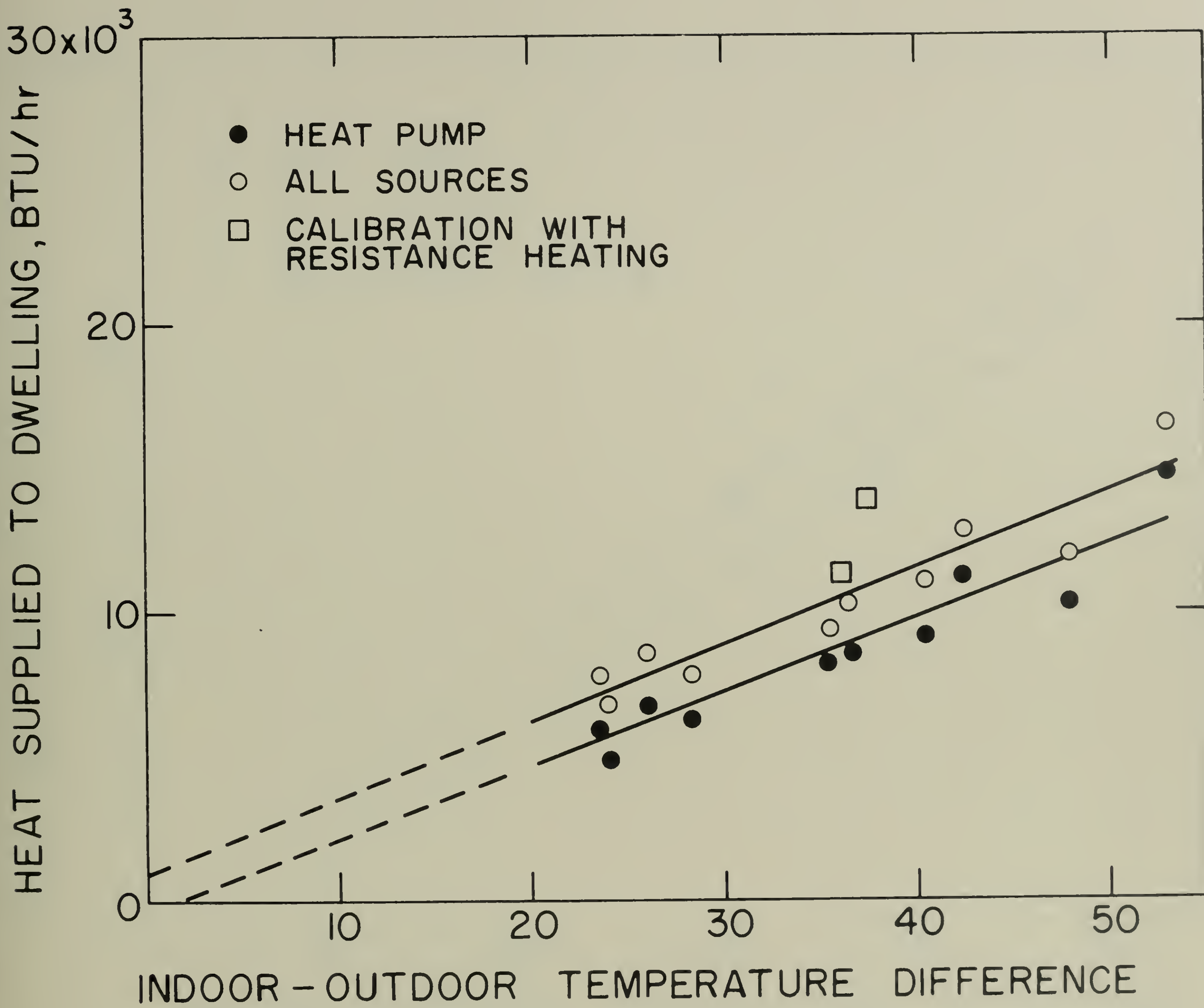

Fig. 61. Heat Supplied to the Type A Dwelling, Seymour Johnson AFB, during Normal Heating for a Range of Outdoor Temperature

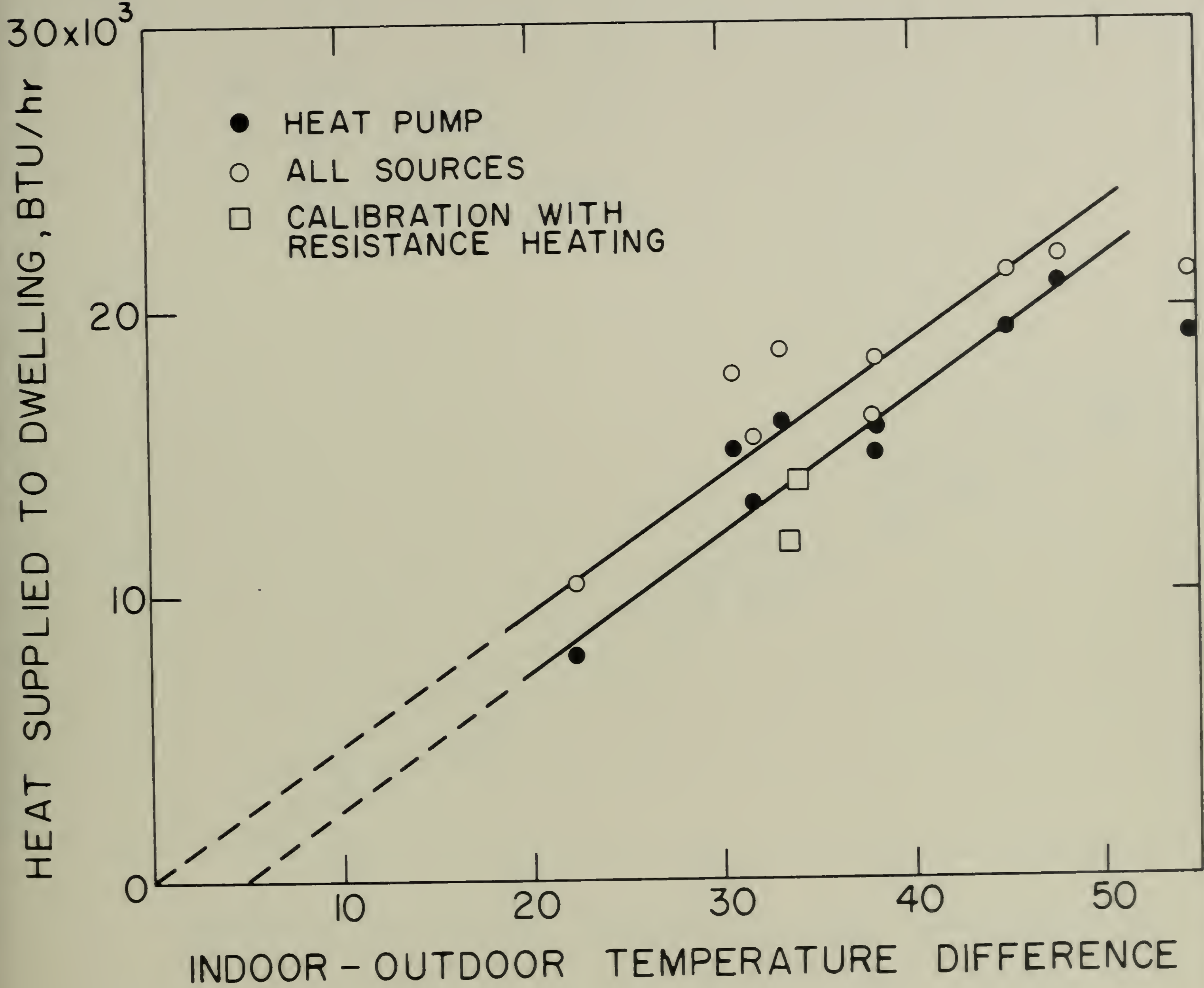

Fig. [illegible]2. Heat Supplied to the Type B Dwelling, Seymour Johnson AFB, during Normal Heating for a Range of Outdoor Temperature

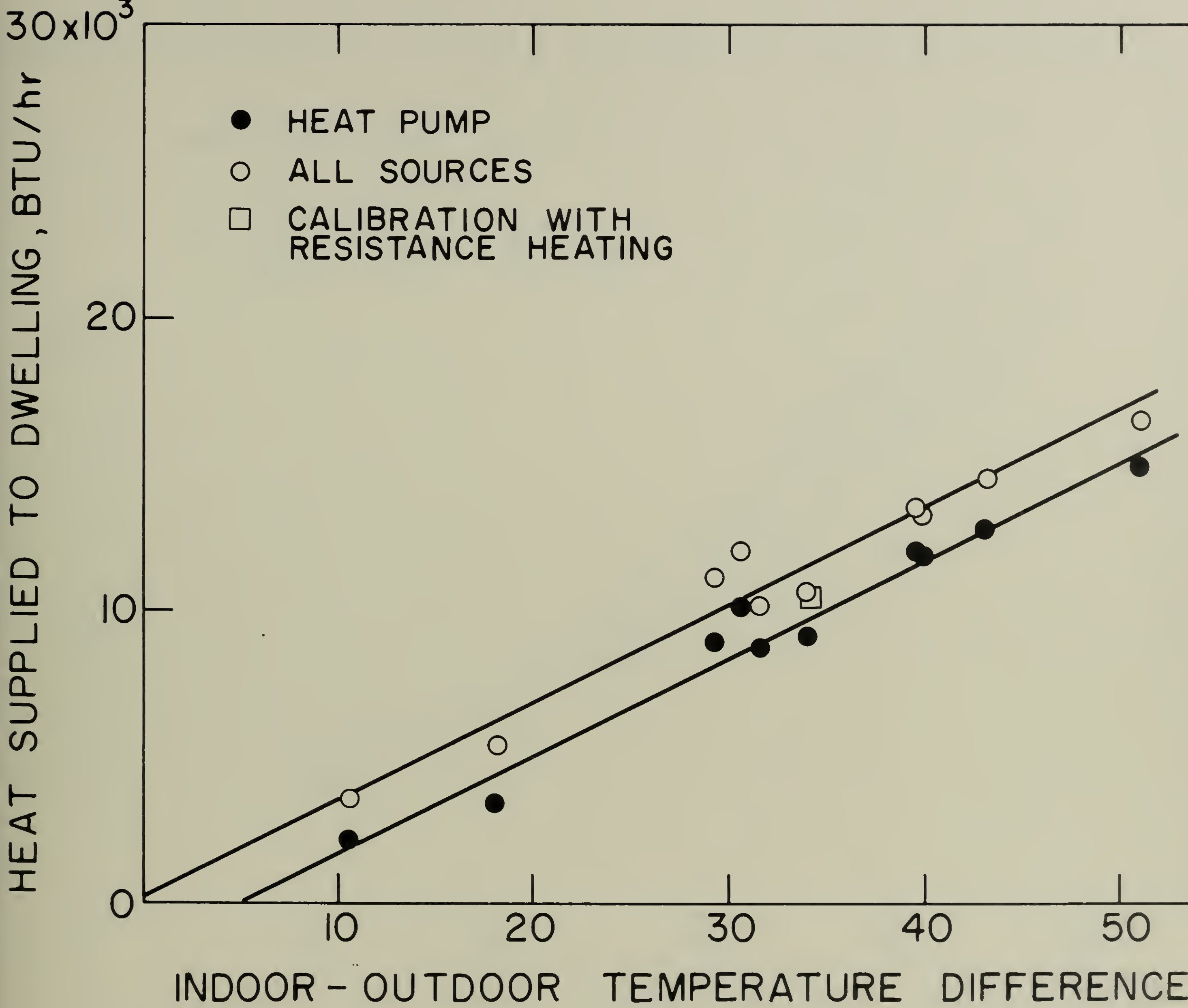

Fig. 63. Heat Supplied to the Type C Dwelling, Seymour Johnson AFB, During Normal Heating for a Range of Outdoor Temperature

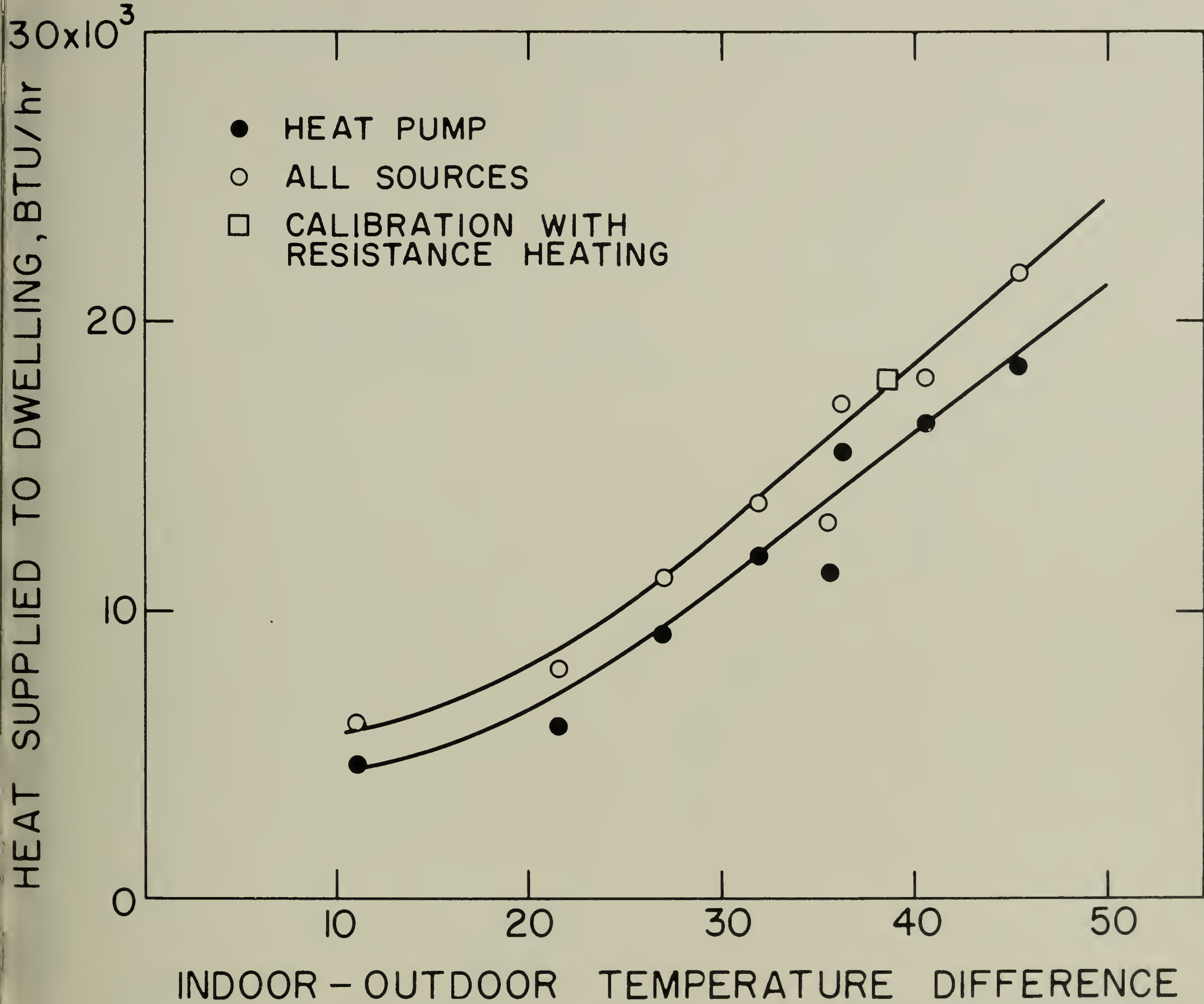

Fig. 64. Heat Supplied to the Type D Dwelling, Seymour Johnson AFB, during Normal Heating for a Range of Outdoor Temperature

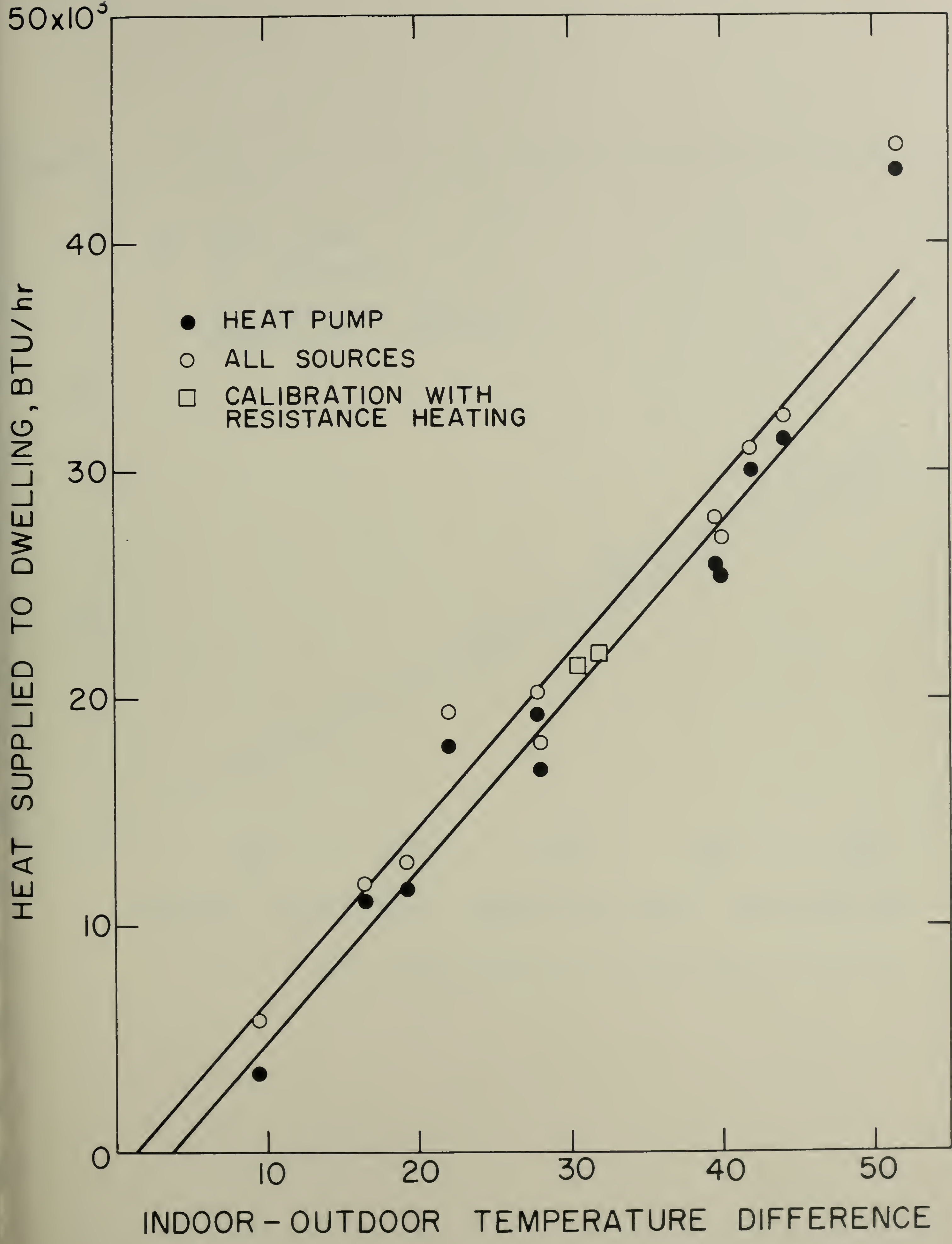

Fig. 65. Heat Supplied to the Type E House, Seymour Johnson AFB, during Normal Heating for a Range of Outdoor Temperature

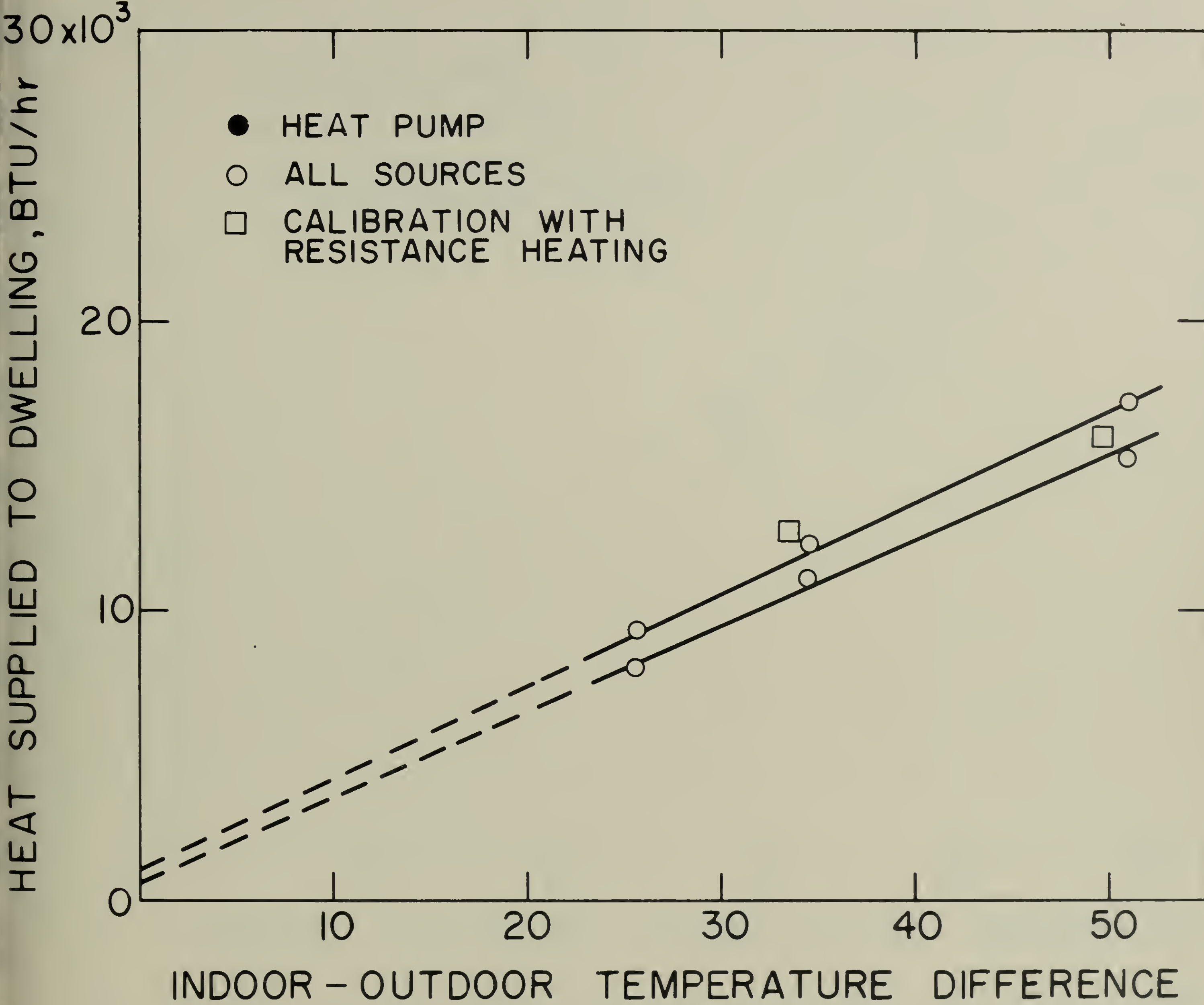

Fig. 66. Heat Supplied to the Type A2D1 Dwelling, Columbus AFB, during Normal Heating for a Range of Outdoor Temperature

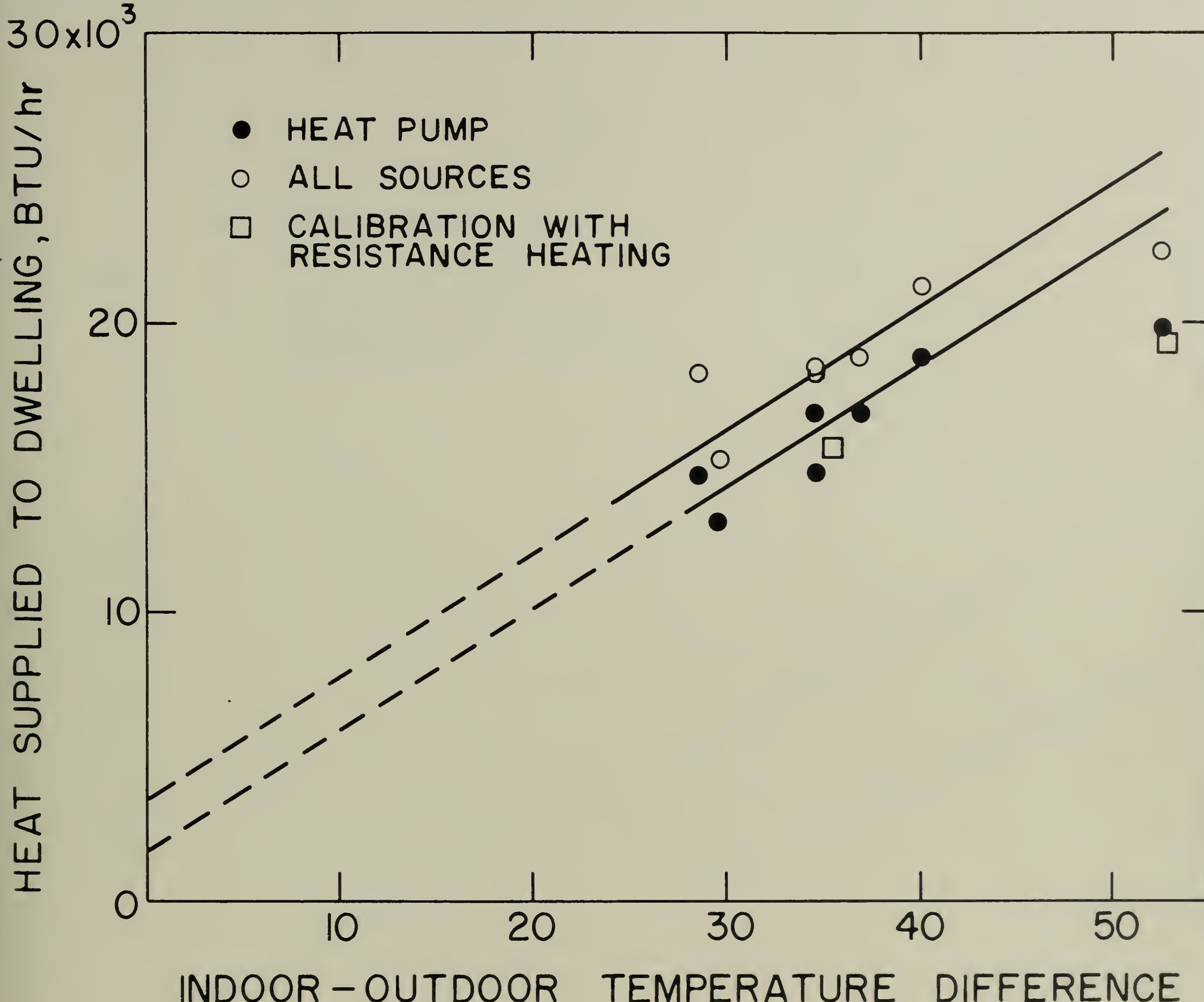

Fig. 67. Heat Supplied to the Type A3D1 Dwelling at 117 Caledonia Loop, Columbus AFB, during Normal Heating for a Range of Outdoor Temperature

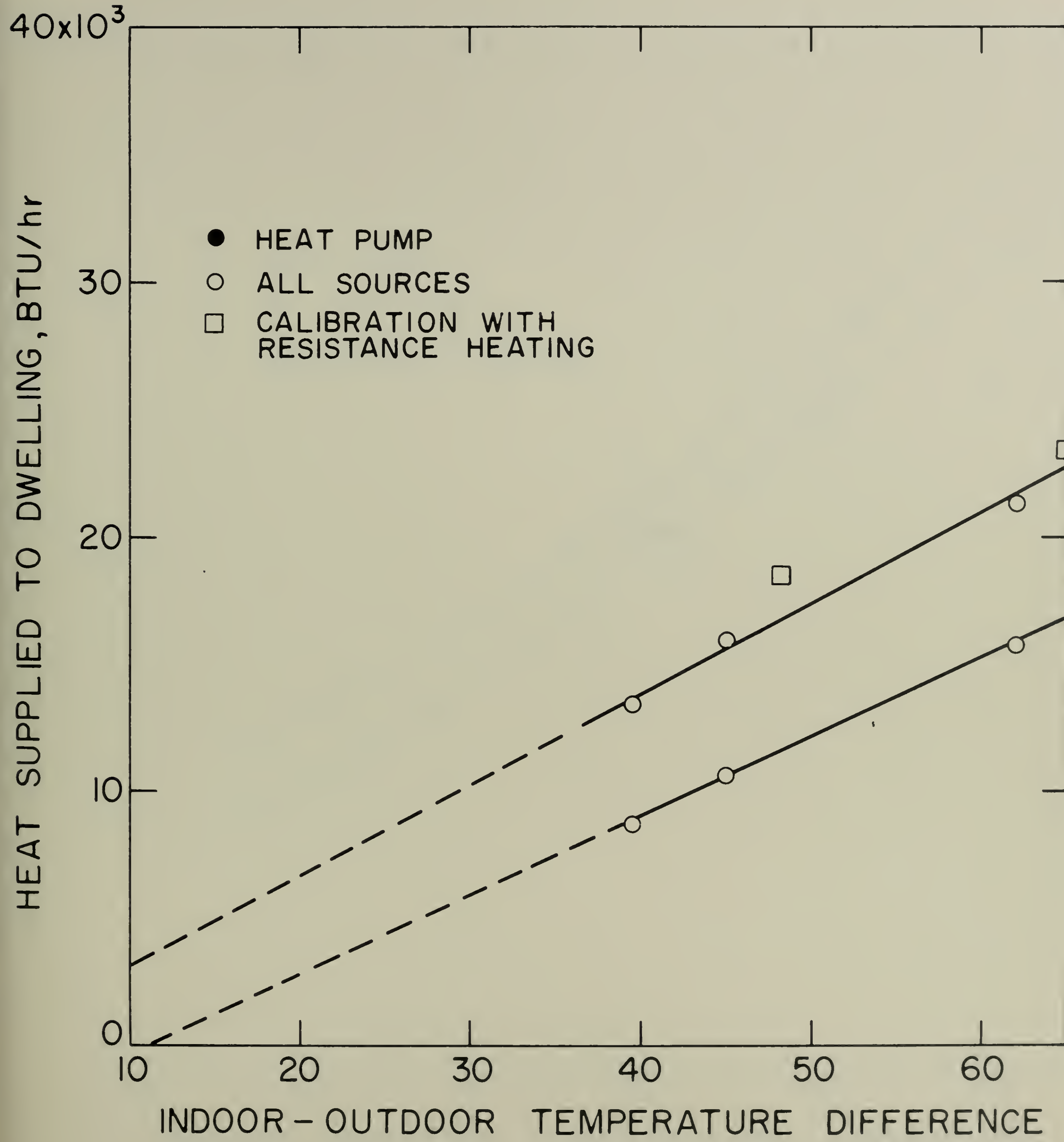

Fig. 68. Heat Supplied to the Type A3D1 Dwelling at 119 Caledonia Loop, Columbus AFB, during Normal Heating for a Range of Outdoor Temperature

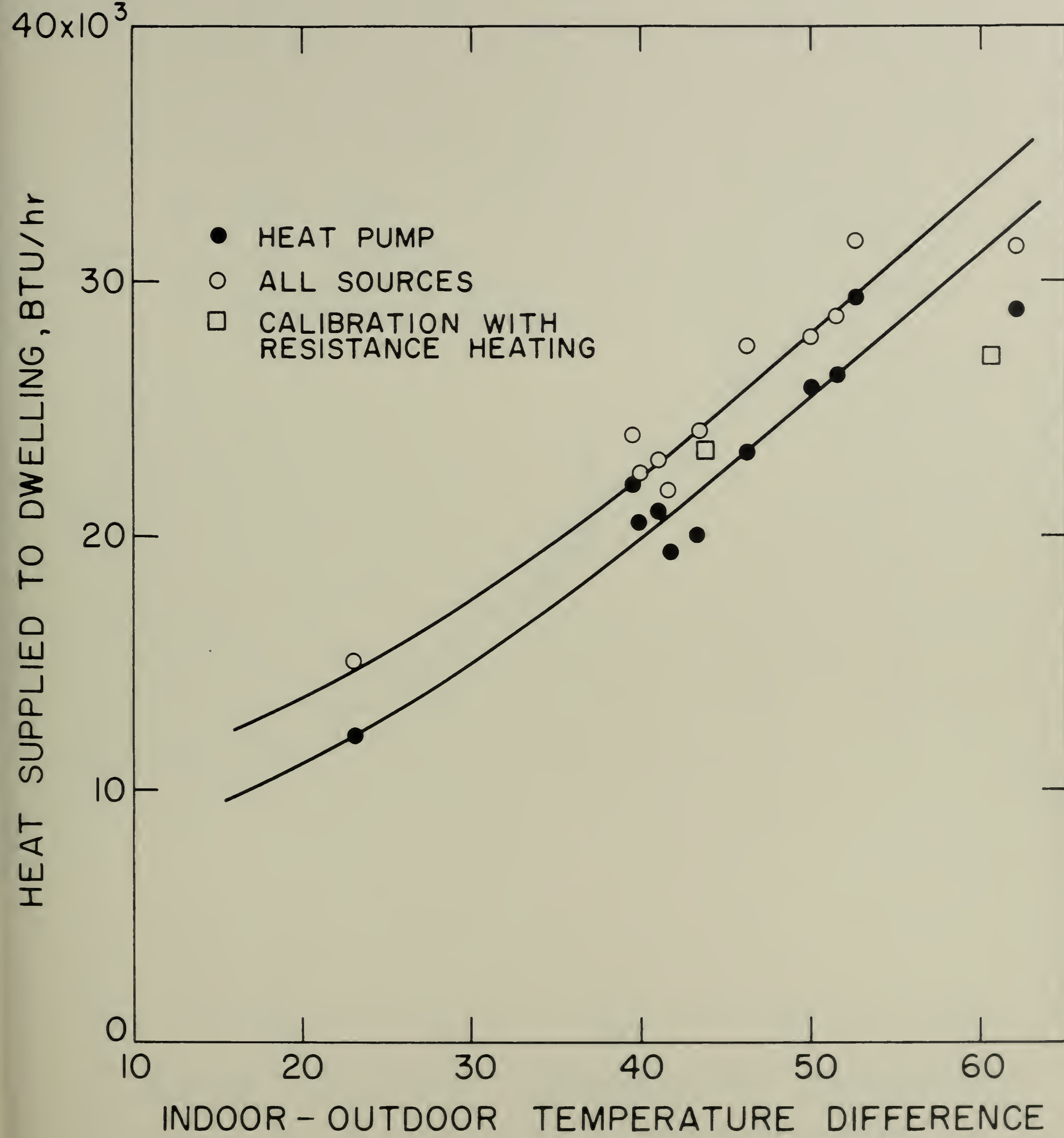

Fig. 69. Heat Supplied to the Type 03S1R House, Columbus AFB, during Normal Heating for a Range of Outdoor Temperature

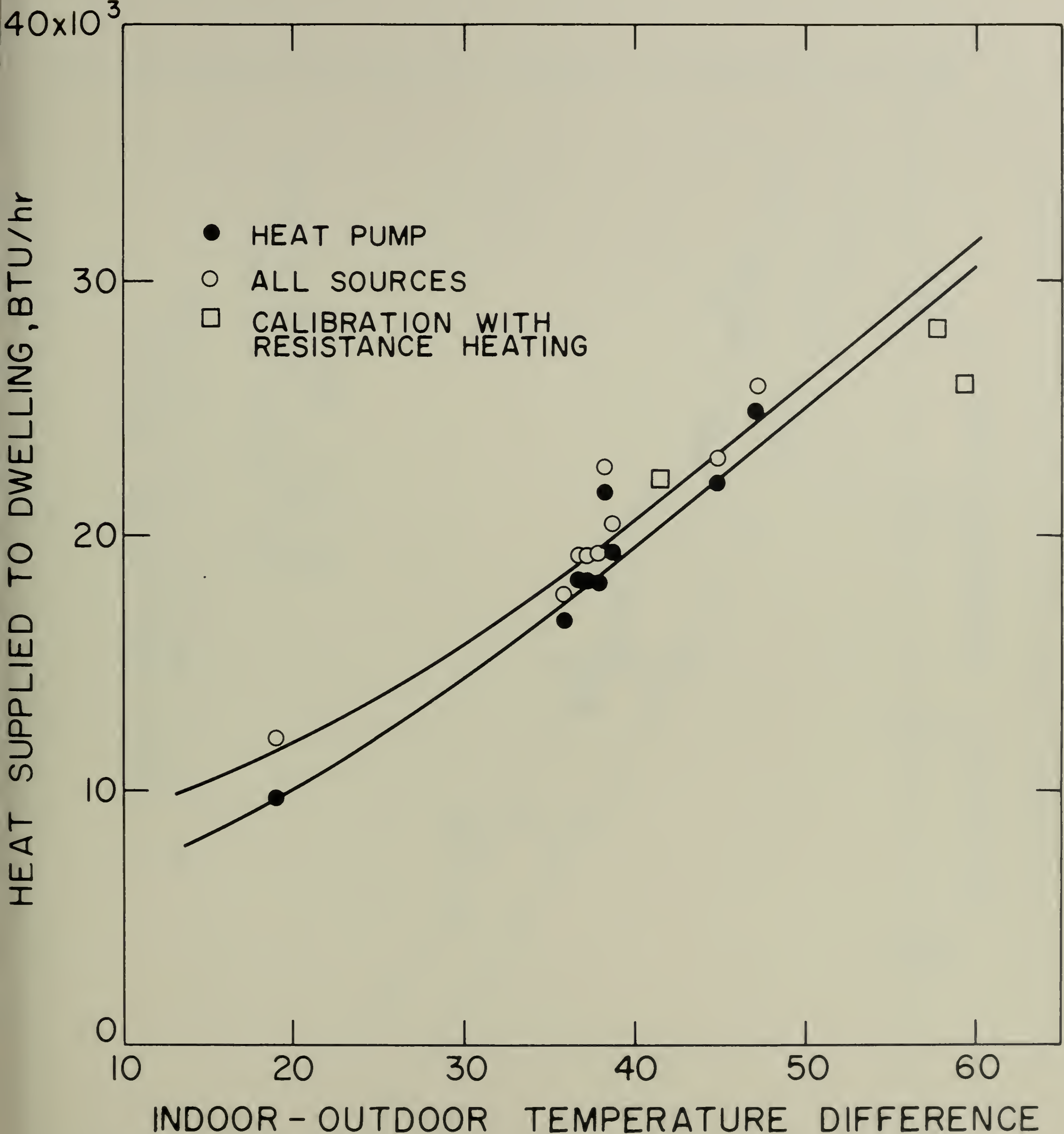

Fig. 70. Heat Supplied to the Type 03S3 House, Columbus AFB, during Normal Heating for a Range of Outdoor Temperature

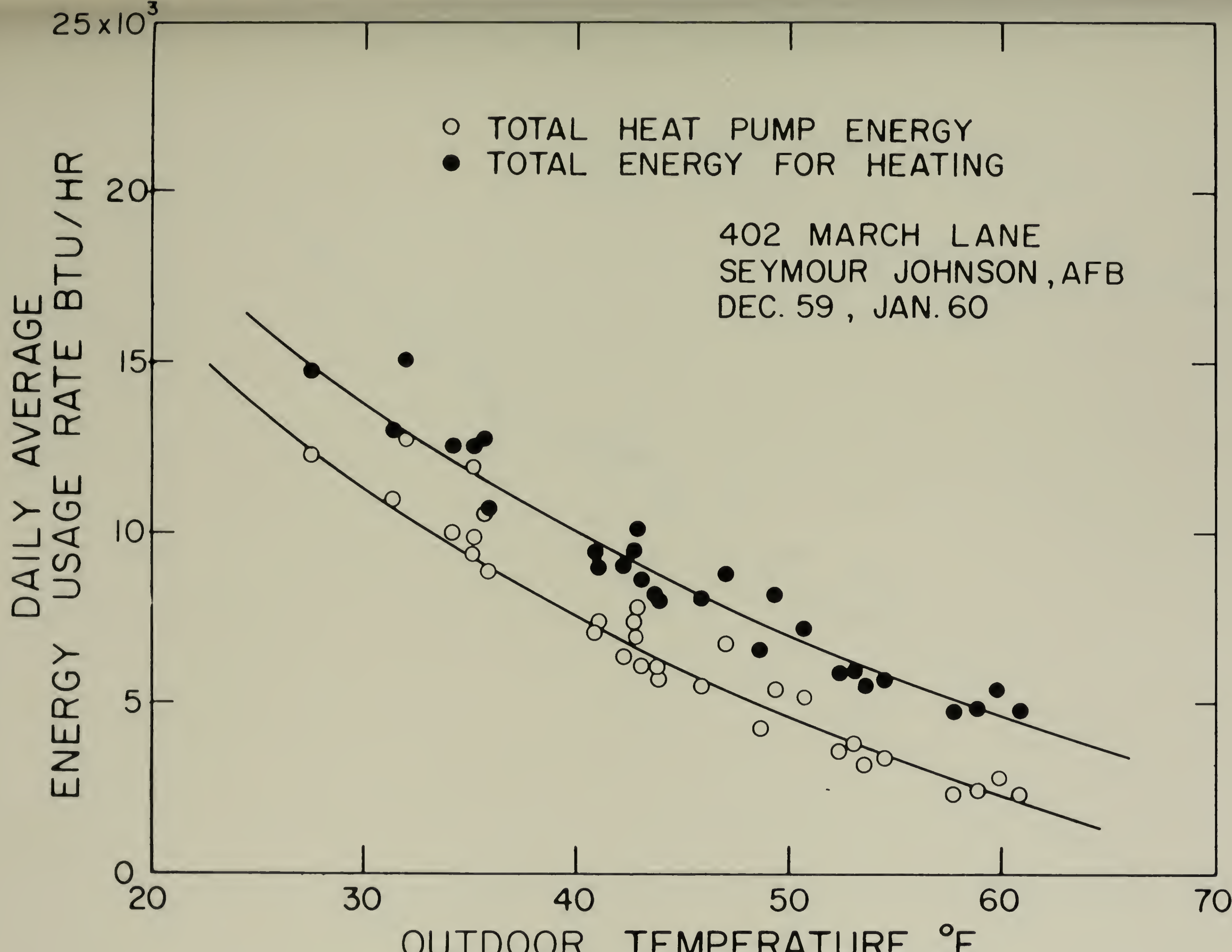

Fig. 71. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type A Dwelling at Seymour Johnson AFB

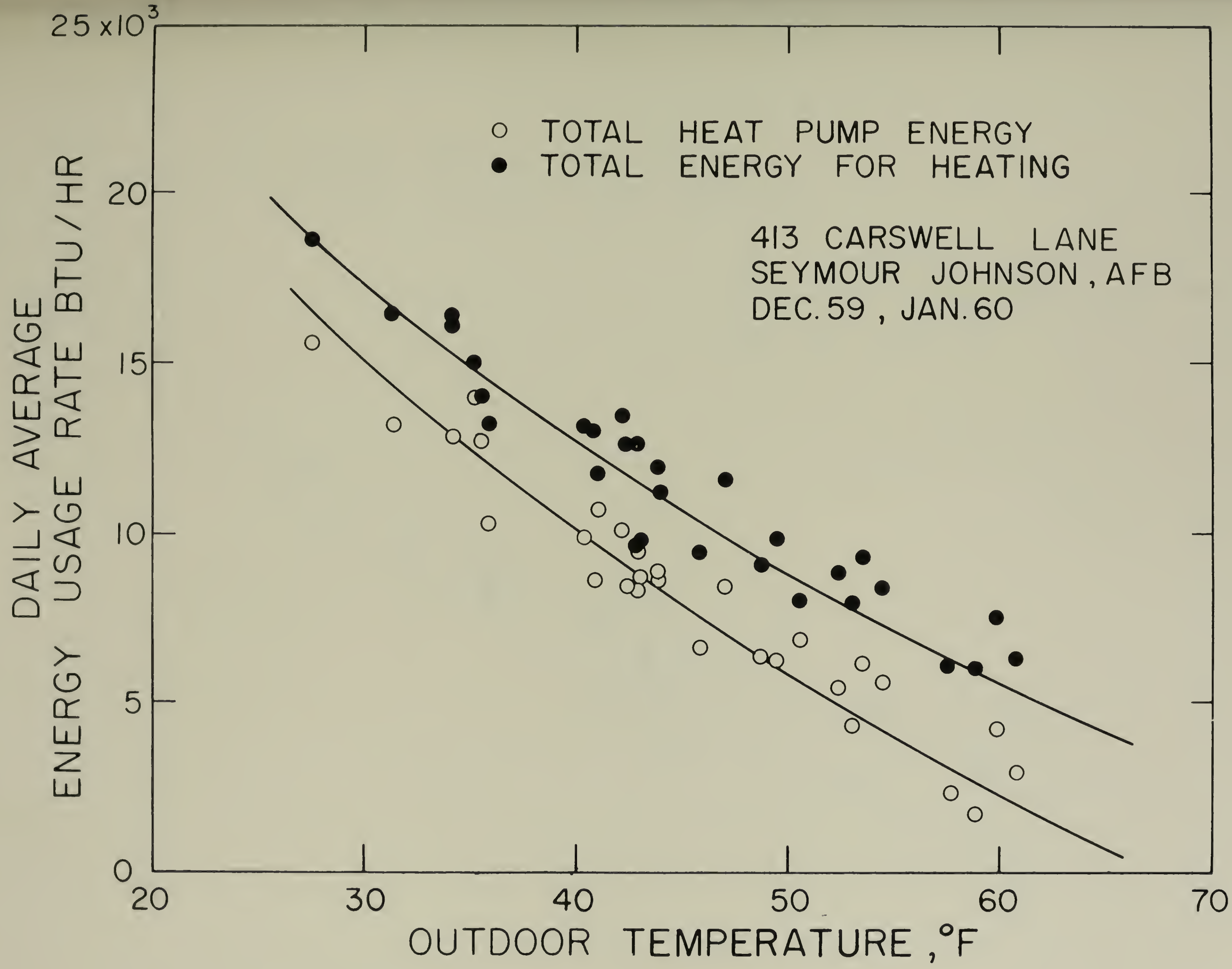

Fig. 72. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type B Dwelling at Seymour Johnson AFB

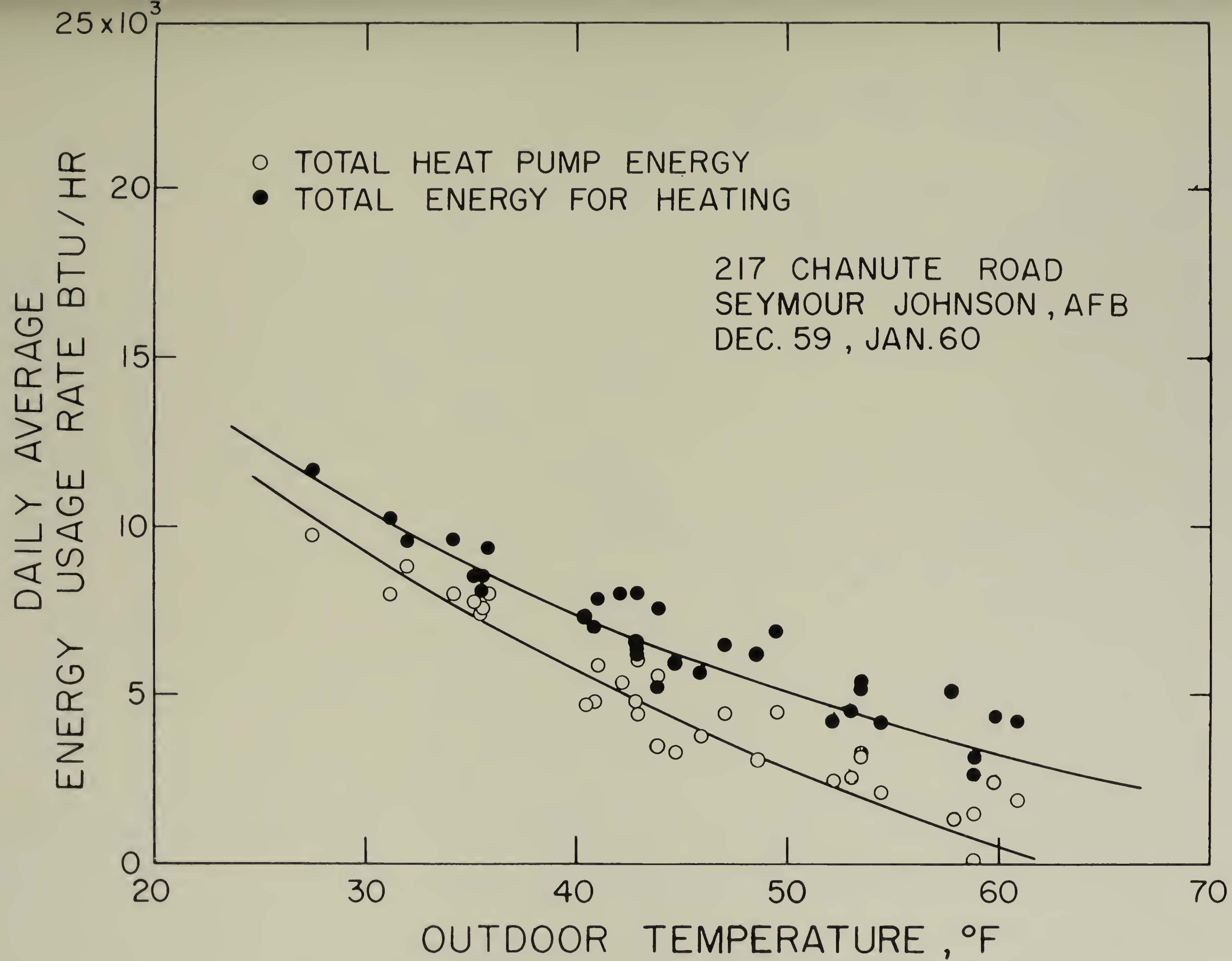

Fig. 73. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type C Dwelling at Seymour Johnson AFB

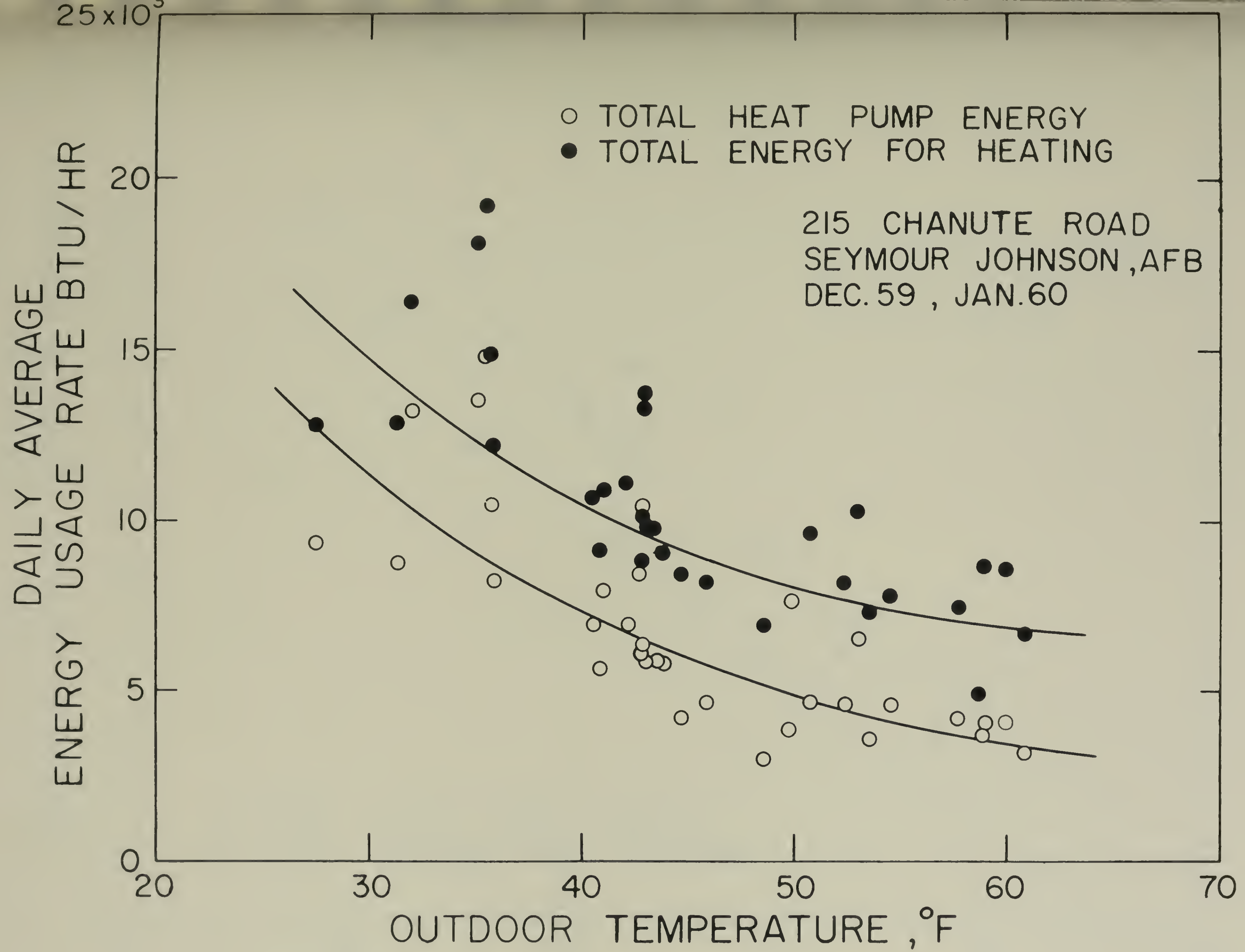

Fig. 74. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type D Dwelling at Seymour Johnson AFB

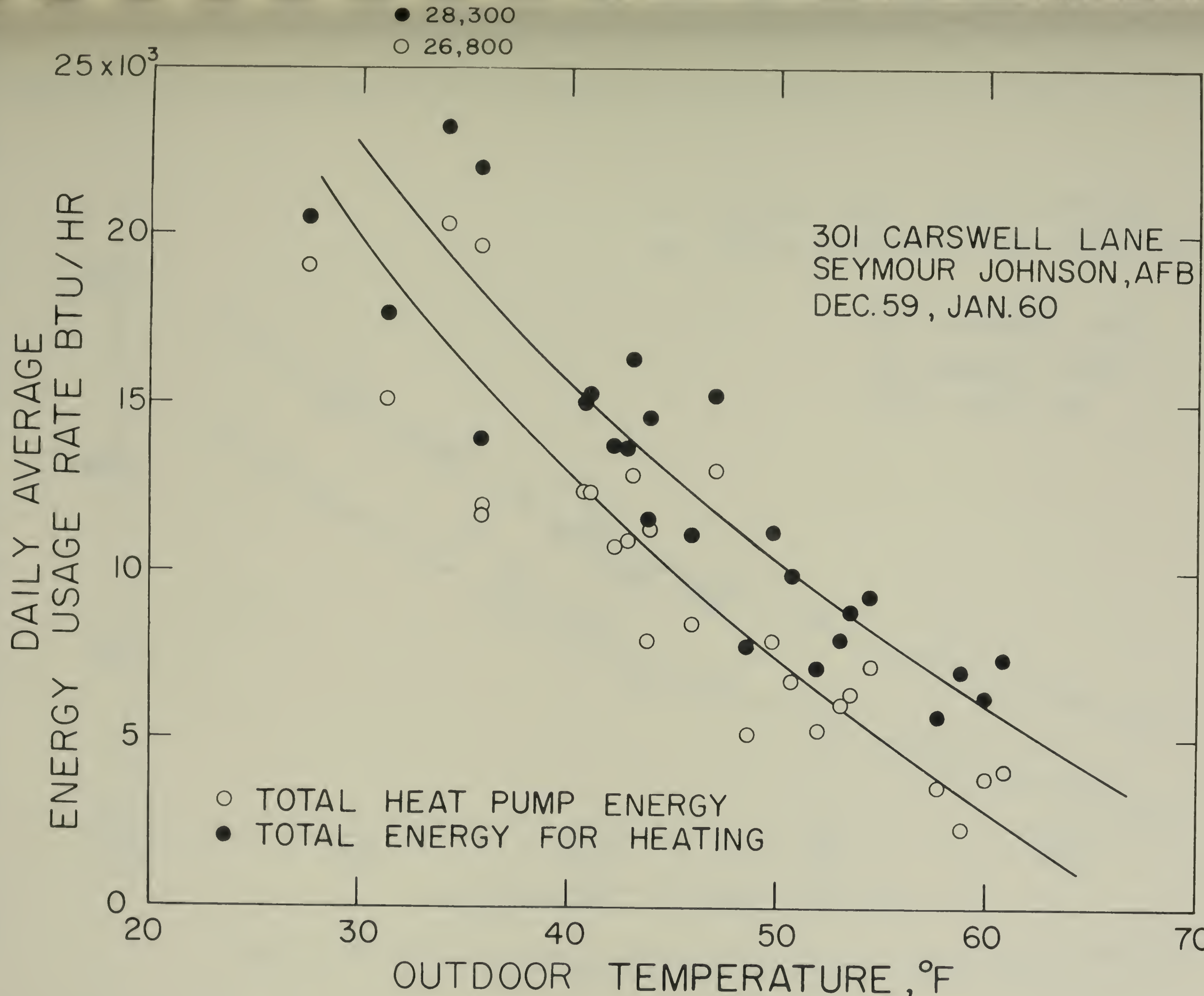

Fig. 75. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type E House at Seymour Johnson AFB

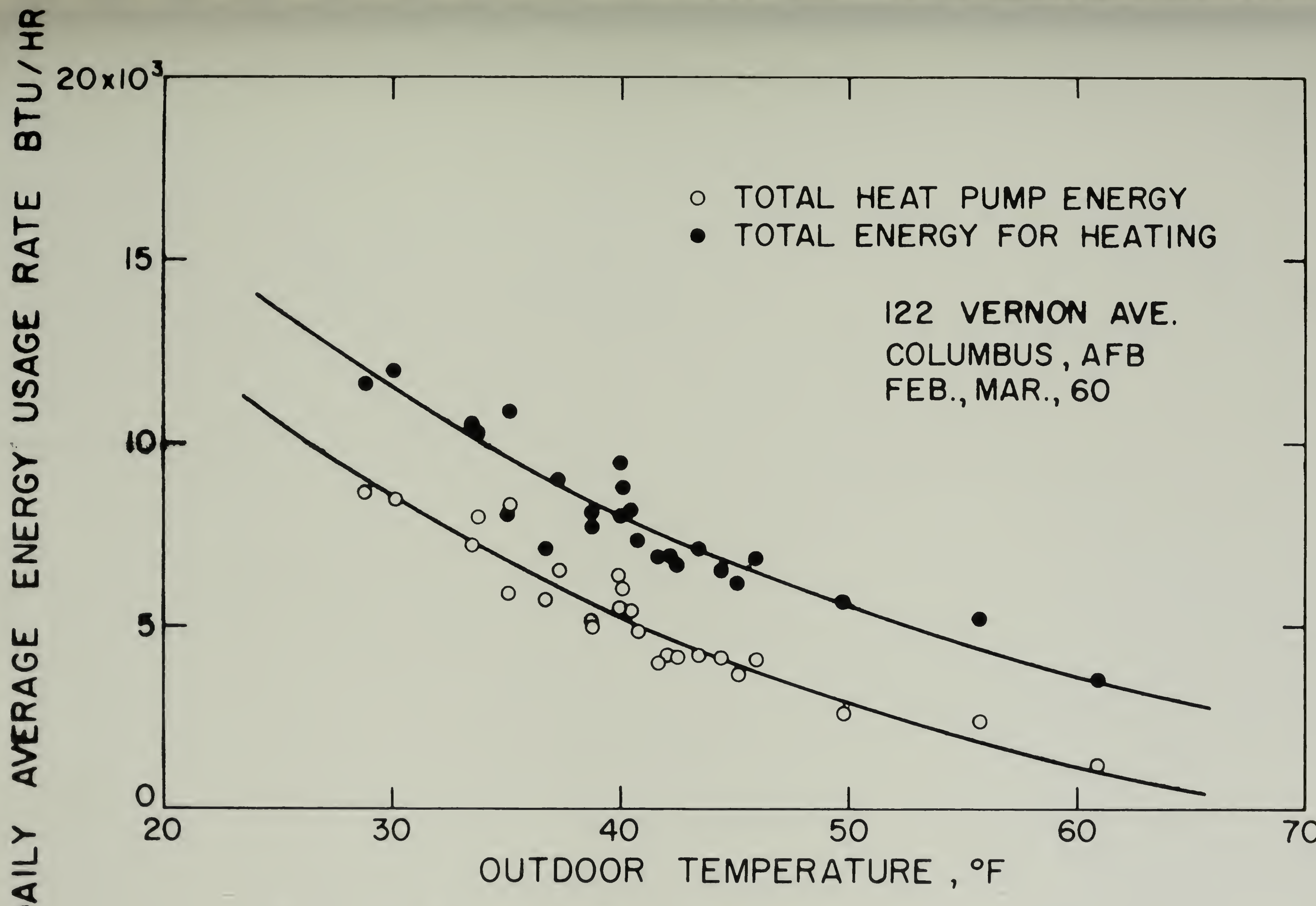

Fig. 76. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type A2D1 Dwelling, Columbus AFB

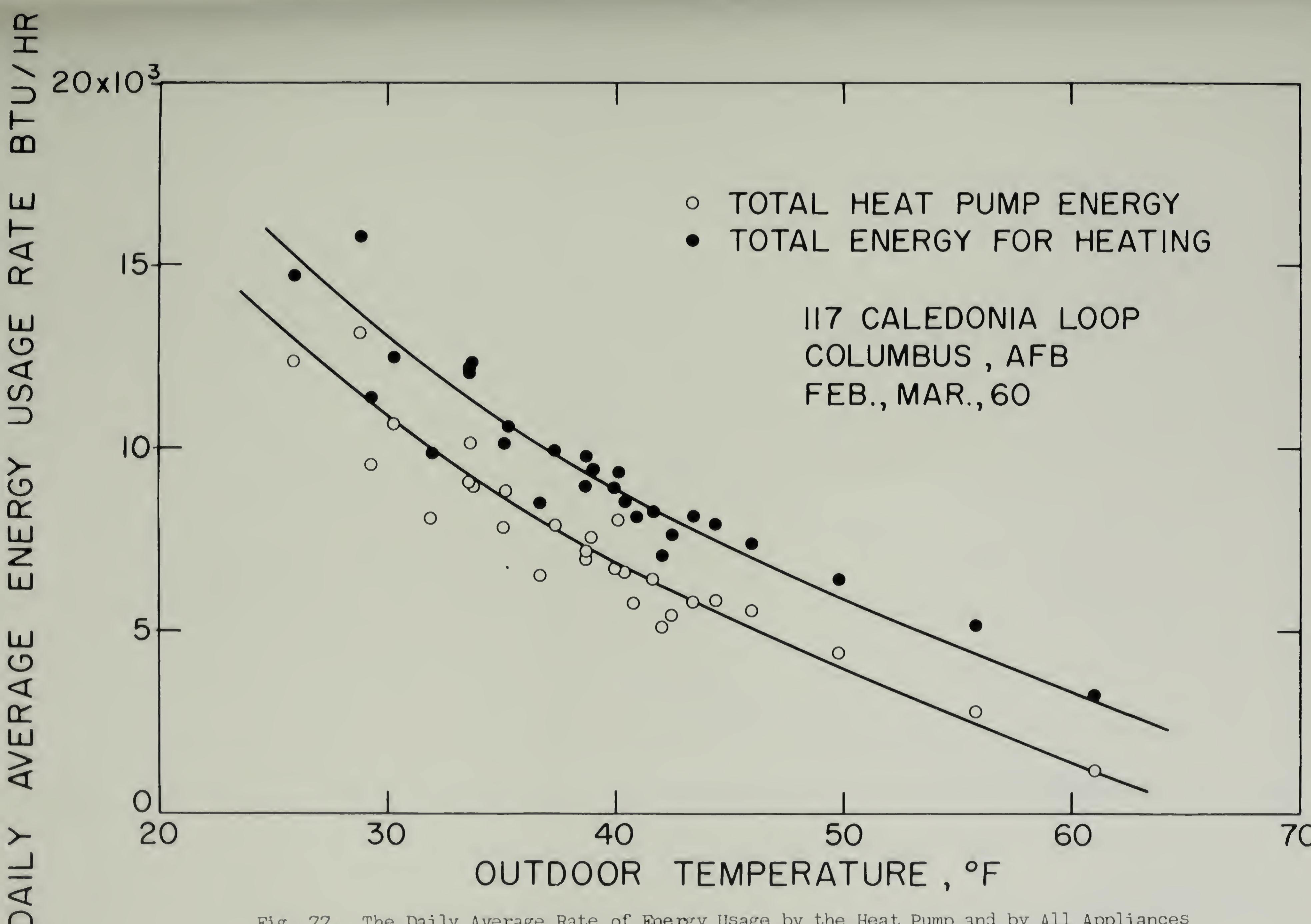

Fig. 77. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type A3D1 Dwelling at 117 Caledonia Loop, Columbus AFB

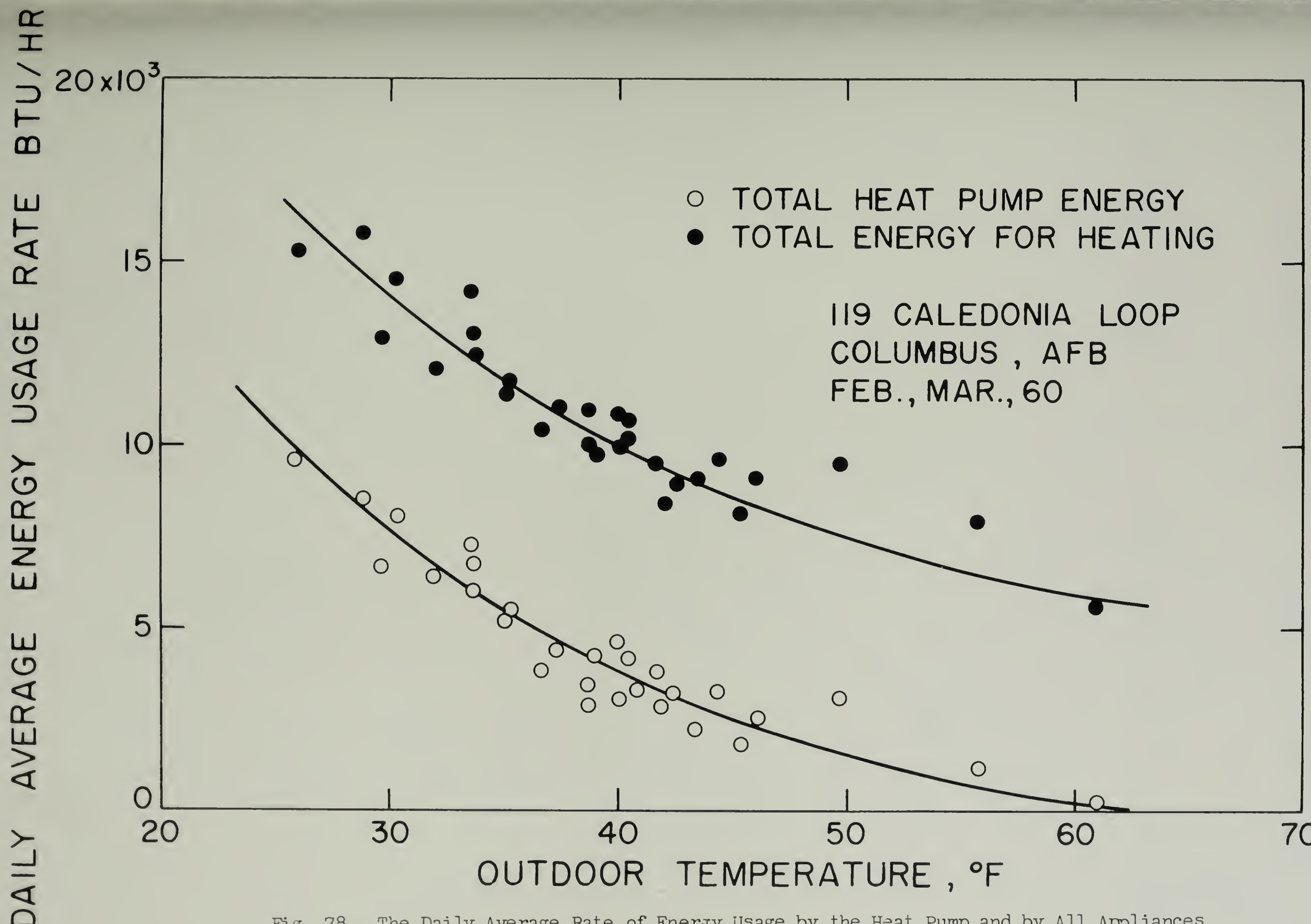

Fig. 78. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type A3D1 Dwelling at 119 Caledonia Loop, Columbus AFB

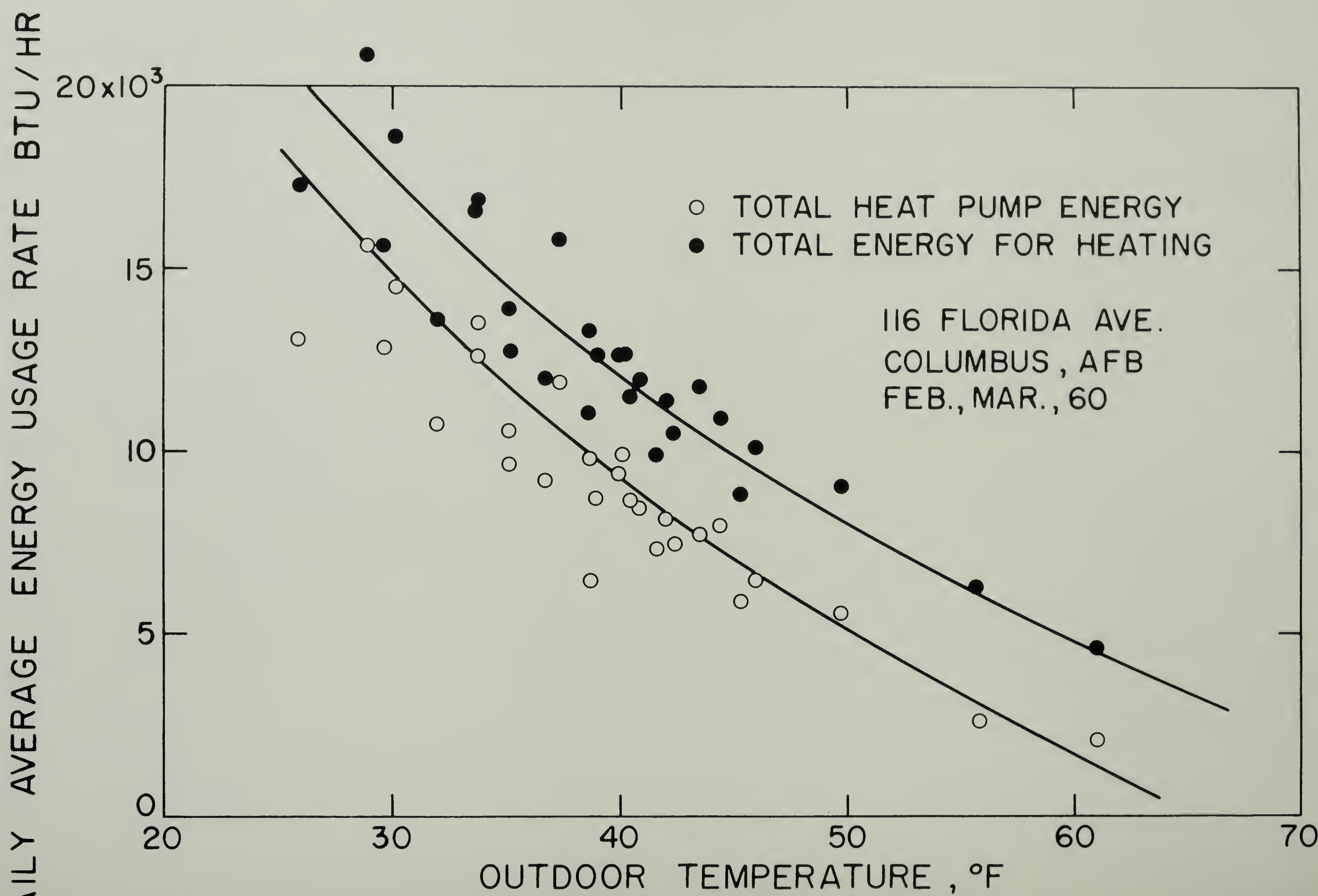

Fig. 79. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type 03S1R House, Columbus AFB

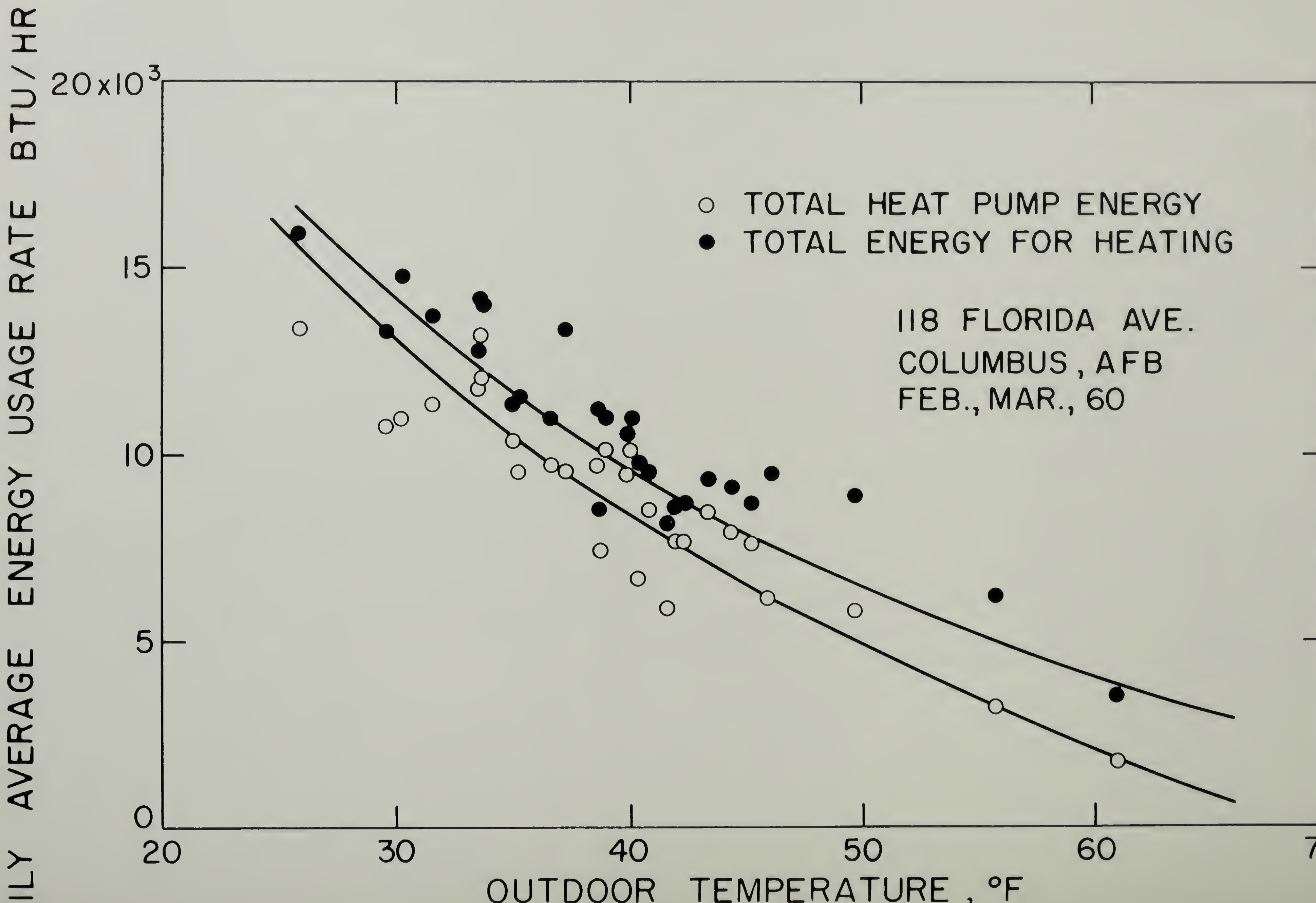

Fig. 80. The Daily Average Rate of Energy Usage by the Heat Pump and by All Appliances for Heating the Type 03S3 House, Columbus AFB

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U. S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D. C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering Laboratory. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

NBS